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Bachelor Thesis

Climbing and Falling Robot: Image Capturing, Transmission and Processing

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Abstract

This thesis deals with the camera that is mounted on the Paraswift robot. The latter is a wall climbing and base jumping robot which can climb a wall, deploy a paraglider on the wall and then fly down and safely land on the ground.

The camera is mounted on a pan/tilt mechanism. It is used to capture images and send these to a laptop on the ground, along with the pan/tilt angles of the camera for every image. A panoramic image is created on the laptop out of the image material by also using the pan/tilt angle information. This thesis especially looks at the enhancement and speeding up of the panorama creation process by using the pan/tilt angle information as an addition to the images.

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Contents

	Abstract	III
	Acknowledgements	V
1	**Introduction**	**11**
1.1	Context & motivation	11
1.2	System overview	12
1.3	Goals	12
1.4	Work packages & time schedule	13
1.5	Preliminary studies	13
1.5.1	State of the art	13
1.5.2	Capture in motion	15
1.5.3	Panorama creation basics	16
1.6	Structure of the report	17
2	**Capturing Concept**	**19**
2.1	Angle of view	19
2.2	Amount of images	20
2.3	Camera motion	21
2.4	Panorama process optimization	23
3	**Camera & Transmission**	**25**
3.1	Camera requirements	25
3.2	Camera choice	26
3.3	AXIS M1011-W	27
3.3.1	Lens	27
3.3.2	Wireless connection	28
3.3.3	Board modifications	28
3.4	Serial data transmission	29

4 Mechanical Design 31
4.1 Requirements . . . 31
4.2 Dimensions & design . . . 32
4.3 Material, manufacturing & weight . . . 32
4.4 Optimization & implementation . . . 33

5 Computer Vision 37
5.1 Existing software . . . 37
5.1.1 One-click stitching . . . 37
5.1.2 Command-line stitching with Panorama Tools . . . 38
5.2 Software development: PanoProcessor . . . 39
5.2.1 Main routine . . . 39
5.2.2 Additional classes . . . 40
5.2.3 Microcontroller program . . . 41
5.2.4 Using PanoProcessor . . . 42

6 Experiments & Results 43
6.1 Captures . . . 43
6.2 PTStitcherNG test images . . . 43
6.3 Stitching with PTStitcherNG . . . 44
6.3.1 Required stitching time . . . 46
6.3.2 Ceiling . . . 47

7 Conclusion & Outlook 49

8 Directories 51
8.1 List of abbreviations . . . 51
8.2 Bibliography . . . 52
8.3 List of figures . . . 53

9 Appendix 55

A Lists, tables and illustrations 57
A.1 Time schedule 57
A.2 Flight dynamics 58

B Data sheets, technical specifications 59
B.1 LENSAGON BVM5015014 lens 59
B.2 AXIS M1011-W camera 60
B.3 AXIS M10 camera series comparison 61
B.4 Antenova Rufa 2.4 Ghz antenna A5839 62

C Software installation 63
C.1 MacPorts 63
C.2 OpenCV 63
C.3 Panotools / Libpano 64
C.4 Hugin 65

D Panoramas 67
D.1 Capture 201104281_1 67
D.2 Capture 201104281_2 68
D.3 PTStitcherNG testimages 69
D.4 Capture 20110513 71

E Source Code 73
E.1 main.cpp 73
E.2 SerialConnection.h 77
E.3 FileManipulator.h 77
E.4 Utils.h 78
E.5 BufferManager.h 78
E.6 CamHandler.h 79
E.7 Settings.h 79
E.8 Microcontroller program 80

1 Introduction

1.1 Context & motivation

The goal of the 2010/11 ETH Focus Project[1] Paraswift[2] is to develop a wall climbing and base jumping robot. Paraswift climbs outdoor building walls and deploys a paraglider, used to safely land on the ground.
Robots often carry around cameras for inspection and other purposes. Likewise does the Paraswift robot; in this case not for inspection but for the attraction of a crowd which looks at the robot in action (see Fig. 1.1 / 1.2). This thesis deals with the camera which gets mounted on the Paraswift robot and the involved mechanisms, electronics and Computer Vision algorithms. The camera is used to create panoramic images from the robots view.

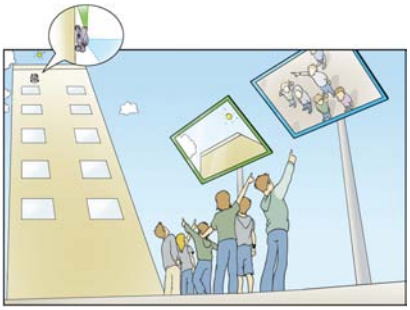


Figure 1.1: Illustration of Paraswift show by Maurizio Nitti, DRZ

Figure 1.2: Paraswift show, 21. June 2011 at ETH Zurich

My personal motivation for this thesis is the variety of different disciplines that are involved. It covers interesting engineering disciplines like mechanics, electronics, computer science/vision and also practical experiments.

[1] Project-based work with other students in the 4th/5th semester of Mechanical Engineering Bachelor at ETH Zurich.
[2] See [12] for more information about Paraswift.

1.2 System overview

As visible on figure 1.3, the Paraswift robot contains a ground plate with vortex adhesion mechanism and gearwheels for driving on the wall (a), a paraglider and it's deployment mechanism (b) and a shell mounted on a protective frame (c). The core of the on-board electronics is a Skybotix[3] CoaX microcontroller.

Figure 1.3: Paraswift robot system overview

1.3 Goals

The following goals were set after the kickoff meeting of this thesis. The minimum "must-have"-goals are:

- Provide an attractive image/video that can be projected on a big screen during presentations of the Paraswift wall climbing and base jumping robot to attract the audience.
- Realise a system containing a camera, video transmitter and receiver, to send image-/video-material from the robot to the ground station, during climbing and flying phase.
- Develop mechanisms to stabilize the camera and remove unwanted effects on the image-/video-material.
- Create one or more panorama images by stitching together multiple single images. Use existing stitching software algorithms.

The "nice-to-have"-goals are:

- Create multiple panorama images in the robots climbing phase, one about every 5-10 meters.

[3] More information on: `http://www.skybotix.ch`

- Map the camera view from the flight phase to the panorama image of the corresponding height, previously taken in the climbing phase.

1.4 Work packages & time schedule

The presented thesis has been structured into 3 main stages: Preliminary studies, concept and implementation.

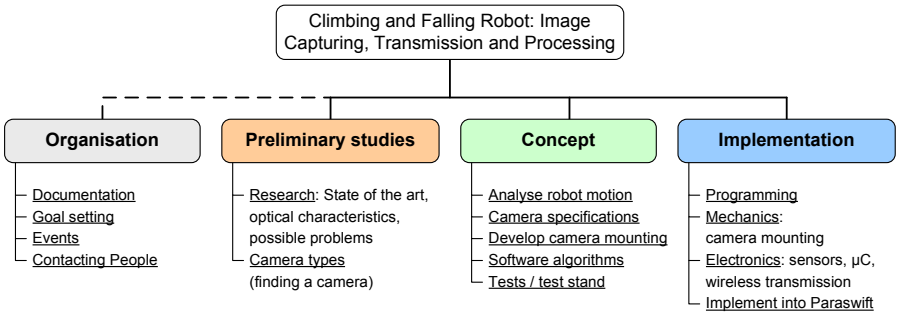


Figure 1.4: Work breakdown structure of the thesis

The stages and work packages (see figure 1.4) have been assigned into a project schedule (see appendix A.1). Together with the detailed schedule, the following milestones have been defined:

- 16.04.2011: Design of camera mounting complete, necessary parts ordered.
- 29.04.2011: Panorama images collected from test stand or test Paraswift robot drop, begin of code-implementation.
- 16.05.2011: First stitch of panorama images with stitching software.

1.5 Preliminary studies

1.5.1 State of the art

A lot of mobile robotic applications use cameras as sensors and to record image/video material (some examples: [10], [11] and [14]). In radio controlled aeroplane toys, cameras are used to transmit the view of the aeroplane directly to the person controlling the aeroplane. This gives to the "pilot" a feeling as if he was sitting in the planes cockpit (FPV - First Person View)[4].

[4] For an example see: `http://www.immersionrc.com`

Most of these systems use analogue video cameras with integrated transmission hardware, which is easy to use, inexpensive and lightweight. When it comes to high resolution and digital transmission, I could not find a camera/transmitter system that is made for live transmission on a lightweight flying device. Wireless (WiFi) cameras are available in the security/video surveillance sector and can be used for this purpose as an alternative.

On the software side, many programs are available on the internet to stick multiple small images together to a large panoramic image. I found that the following applications might be useful for panorama stitching and viewing:

- Autostitch, fully automatic panorama stitcher
  `http://cvlab.epfl.ch/~brown`
- Hugin, open-source panorama stitcher GUI for Panotools
  `http://hugin.sourceforge.net`
- Panotools ("Panorama Tools"), free and partly open source panorama libraries, tools and applications
  `http://panotools.sourceforge.net`
- PTGui, panorama stitcher GUI application for Mac / Windows
  `http://www.ptgui.com`
- Calico Panorama 2, Panorama stitcher GUI application for Mac OS X
  `http://www.kekus.com/beta`
- PTStitcherNG, Panorama stitcher optimized for speed and batch processes
  `http://webuser.fh-furtwangen.de/~dersch/`
- Panosalado 2, a Flash 10 panorama viewer
  `http://os.ivrpa.org/panosalado/`
- Windows Live Photo Gallery, photo gallery application with panorama functionality
  `http://explore.live.com/windows-live-photo-gallery`

A few of these applications have been evaluated (see chapter 5.1).

1.5.2 Capture in motion

This chapter describes a few camera and capturing related issues that are important when using a camera that is in motion during image/video capturing.

The amount of light going through the camera opening is called **exposure** and is measured in lux seconds. The opening is called **shutter** - the duration during which the shutter is open is called **exposure time** and is controlled by the shutter speed. With a short exposure time it is possible to record a moving object without **motion blur**, but can create a dark image because less light gets on the camera's image sensor. A longer exposure time allows to record a scene over a period of time, although moving objects may get motion blur (see figure 1.5 for an example). [2] [3] [4]
In order to create good looking panorama images, motion blur has to be avoided. Chapter 2.3 shows an approach to do so.

Figure 1.5: Example image with motion blur [3]

Figure 1.6: Example image showing the effect of rolling shutter [6]

Figure 1.7: Example image (interlaced) [9]

Figure 1.8: Example image (progressive scan) [9]

Cameras with **global shutter** record every point / pixel of a frame in the same period of time. In contrast **rolling shutter** (also called line scan) scans across a frame line by line either vertically or horizontally over a period of

time. This effect gets visible when recording moving objects or moving the camera while recording: The scene changes slightly for every recorded line which results in a distorted image (see figure 1.6 for an example). [6]

Interlacing (interlaced video) is a method of refreshing odd and even horizontal lines of a video alternately. It allows doubling of the perceived frame rate but requires playback equipment that supports de-interlacing (mainly CRT screens). The **progressive scan** method scans an image line by line going from top to bottom, treating odd and even lines equally. See figures 1.7 and 1.8 for examples. [8] [9]

1.5.3 Panorama creation basics

For captured image material to stitch successful to a panoramic image, panoramic heads are used in photography (see [13] for examples). These special camera mountings rotate the camera exactly around it's focal point to eliminate parallax error in the stitching process. When not rotating the camera around it's focal point, the ratio of the camera translation to the scene distance should be kept small for the error to be negligible.

On the software side, stitching together image material can take a long time (depending e.g. on the image amount, the image resolution and the used hardware). Most panorama creation applications detect control points on all images and compare images with each other by comparing the matching of their control points. This process requires an overlapping area of the images (50% should be sufficient as a guideline) and images with adequate texture so control points (e.g. edges) can be detected. By not knowing initially which image is located about where in the final panorama, the control points of all images have to be compared with the control points of all other images. See figure 1.9 for a control point comparison illustration.

Figure 1.9: Control point comparison illustration from Autopano Pro GUI http://www.kolor.com/panorama-software-autopano-pro-interface.html, requested: 25/06/2011

1.6 Structure of the report

The report is structured into the following chapters. The Introduction gives a brief intro about this thesis. It is followed by the "Capturing Concept" which explains the way images will be captured. The chapter "Camera & Transmission" explains about the electronics used in this project. In the chapter "Mechanical Design", the design of the pan/tilt camera mounting is documented. The chapter "Computer Vision" contains software evaluation and documentation of the coding work. In the chapter "Experiments & Results", the field experiments and their outcome are presented. Finally the chapter "Conclusion & Outlook" concludes the thesis and contains ideas of further use and improvements of the work of this thesis.

2 Capturing Concept

This chapter describes the concept for the creation of panorama images.

2.1 Angle of view

The angle of view of the camera lens (sometimes also referred to as field of view) defines how large the angular visual extent of the camera is. [5] The maximum angle of view has been derived in the following way:
A persons face in the audience of the Paraswift show should have a vertical resolution of around 22 pixels (see figure 2.1) at a distance of $15\,m$ to the camera. With an average face height of $20\,cm$ a proportional calculation leads to the fact that 480 pixels (assumed vertical camera resolution) would display $\approx 4.5\,m$ vertically.

Figure 2.1: Example portrait with 22 pixels "face resolution".

Figure 2.2 shows the basic arrangement of the geometrical calculation. Thus the minimal vertical angle of view is:

$$\alpha = \frac{H}{l} = \frac{y_{res} \cdot h}{f_{res} \cdot l} = \frac{480 \cdot 20cm}{22 \cdot 15m} = 16.7°$$

With: $f_{res} = 22$ (vertical face resolution in pixels)
$y_{res} = 480$ (vertical camera resolution in pixels)

The following assumptions were taken into account:

- Distance from the camera to the face in the audience during the whole show: $l = 15\,m$
- The distance l is much larger than the face height: $l >> h$
- Average face height: $20\,cm$
- The used camera has a resolution of 640x480 pixels and thus an aspect ratio of 4:3

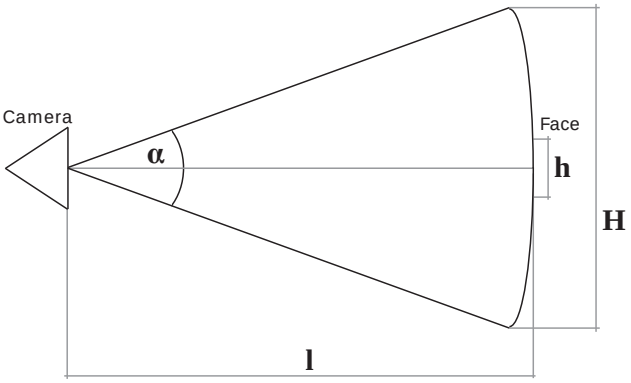


Figure 2.2: Geometrical calculation of the angle of view.

This leads to a horizontal angle of view of about $\alpha \approx 20°$ with an aspect ratio of 4:3.

2.2 Amount of images

In chapter 2.1, the required horizontal angle of view of the camera lens was derived as $\approx 20°$. Because the robot is mostly on a horizontally linear shaped wall, the maximum image width angle is about 180°. With an overlapping image width angle of 10° (50%) per image, the required amount of images horizontally is derived as follows:

$$n_{img_h} = \frac{total\ angle}{angle\ of\ view - overlapping\ angle} = \frac{180°}{20°-10°} = 18$$

In the same way, it is possible to calculate the required amount of images vertically, with a vertical angle of view of $\approx 16°$ (see chapter 2.1) and the overlapping image height angle of 8°. The maximum image height angle is chosen as $\frac{9}{16} \cdot 180° \approx 100°$ with the supposition of a 16:9 cinema aspect ratio for the final panorama image.

$$n_{img_v} = \frac{total\ angle}{angle\ of\ view\ -\ overlapping\ angle} = \frac{100°}{16°-8°} \approx 12$$

Figure 2.3 shows the amount of images that have to be captured horizontally and vertically. In total, one panorama image will consist of about $18 \cdot 12 = 216$ images.

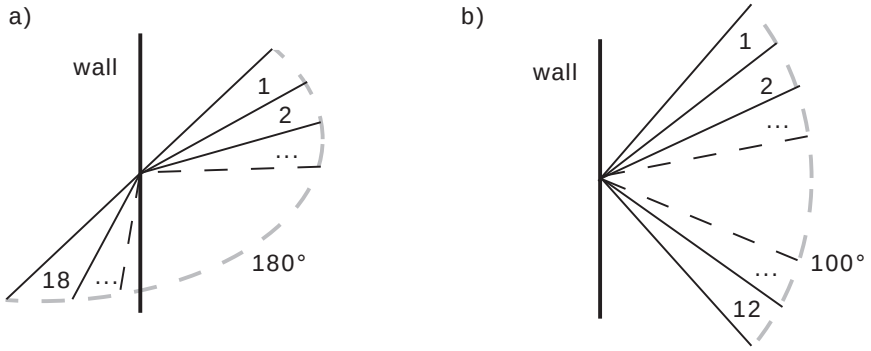


Figure 2.3: Amount images to be captured (a) horizontally and (b) vertically

2.3 Camera motion

The Paraswift robot reaches a climbing speed of $\approx 15\,\frac{cm}{s}$ and will climb at least 12 meters up the wall.[1] I defined that every 4 meters there should be issued one panorama image, made of the 216 single images. The time available to create the images is $t = \frac{4m}{0.15\frac{m}{s}} = 26.7\,s$ assuming the image material can be captured during climbing and the Paraswift robot climbs at full speed. The camera will move with the following angular velocity under the assumptions above:

$$\omega \approx (n_{img_v} \cdot (180° - 20°) + (100° - 16°)) \cdot \frac{\pi}{180°} \cdot \frac{1}{t}$$
$$\omega \approx (12 \cdot 160° + 84°) \cdot \frac{\pi}{180°} \cdot \frac{1}{26.7s} = 1.36\,\frac{rad}{s}$$

Assuming the camera is the reference system, objects at a distance of $15\,m$ will move with $\approx 15\,\frac{m}{s}$ relative to the camera. When recording a moving scene, motion blur (see chapter 1.5.2) can become a problem. It is in this case an unwanted, but also removable effect.[2] To avoid motion blur, the shutter speed of the camera has to be fast enough.

[1] According to the requirements of the Paraswift robot in [12]
[2] See [1] (P. 141) and [15] for details

The shutter speed can be calculated in the following way. Assumptions:

- An object moves horizontally with $15\,\frac{m}{s}$
- Horizontal resolution of the camera: 640 pixels
- Distance from the camera to the object: $15\,m$
- Horizontal angle of view of the camera lens: $20°$

The horizontal resolution of 640 pixels depicts $2 \cdot 15\,m \cdot tan(10°) \approx 5.3\,m$ of a scene with moving objects. Therefore one pixel depicts $8.28\,mm$. If an object moves with $15\,\frac{m}{s}$, it moves with $\frac{15\,\frac{m}{s}}{8.28\,mm} \approx 1800$ pixels per second. Thus the required shutter time is $\frac{1}{15\frac{m}{s}/8.28\,mm} \approx \frac{1}{1800}s$ in order to have a zero pixel motion blur (no motion blur at all).

The Paraswift robot and hence the camera also swings during the down flying phase. According to earlier collected and analysed Paraswift video material[3], the robot swings primarily around the tilt/pitch axle[4]. Figure 2.4 illustrates the swinging over time. The experimentally determined swinging curve has a maximum at around 1 second after robot drop of $68°$ and a minimum at about 2.25 seconds after robot drop of $-18°$.

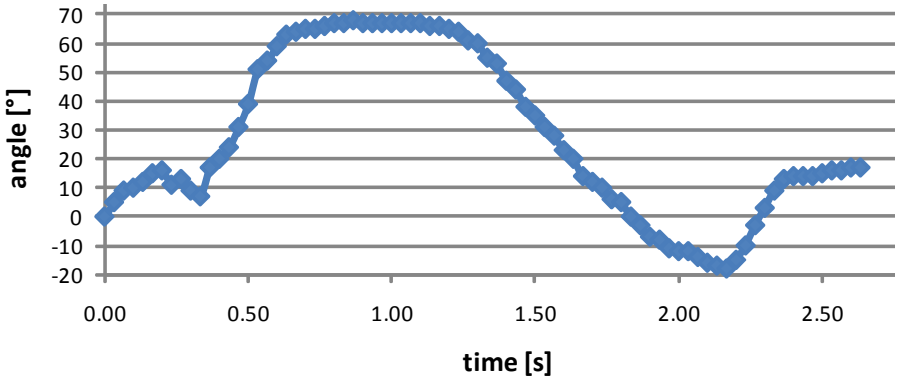


Figure 2.4: Swinging angle of the down flying Paraswift robot around the tilt/pitch axle

This motion requires the camera to be able to move at least $|68°|+|-18°| = 86°$ around the tilt/pitch axle in order to always keep one point focused. With the defined minimal tilt/pitch motion of 100° in chapter 2.2, this request is fulfilled.

[3] Paraswift video P1000393_Steuern_1915_19.mov from testing session 2010-12-09_1_CamLukasG_Steuern_Hoenggerberg

[4] See Appendix A.2 for a description of the different axles

2.4 Panorama process optimization

Generally said, the two important times which are relevant for the panorama creation process are $t_{capture}$ and t_{stitch}. $t_{capture}$ is the required time to capture all the images required for one full panorama image. t_{stitch} is the time required to stitch the images together to the panorama. $t_{capture}$ is restricted to a certain extent to prevent motion blur (see chapter 2.3). t_{stitch} is restricted by the used software and hardware and thus can be optimized by tuning especially the software part.

3 Camera & Transmission

3.1 Camera requirements

The requirements for the camera have been defined as follows:

- Camera / transmitter total weight: $< 100\,g$
- Camera resolution of at least 640x480 pixels
- Digital transmission (or analogue with a frequency other than 2.4 Ghz)
- Horizontal angle of view of 20° or removable objective (see chapter 2.1)
- Fit in available space (see chapter 4.1 and figure 4.5)
- Shutter time of at least $\frac{1}{1'800}\,s$ to avoid motion blur (see chapter 2.3)

The camera weight was already chosen to be $< 100\,g$ at an early stage of the Paraswift project. For a flying robot it is very important that the weight is kept low.

The resolution requirement was set because this is a resolution which could be achieved with a cheap analogue camera/transmitter too, to have this option open as a backup plan.

A transmission frequency of the camera other than 2.4 Ghz is required to avoid interference with the radio that controls the Paraswift robot. This does mainly apply to analogue transmitters, because they spread their signal with bad affect on other devices on this frequency, as I was told by people working with similar components. A digital transmission can have any frequency as it wont interfere with the robot's radio.

3.2 Camera choice

After searching the internet for many different cameras and testing a possible analogue camera that was already available at the lab, the decision was made to focus on a WiFi surveillance camera because they seem to work well for the purpose. Table 3.1 shows a closer selection of WiFi cameras which are light and meet the requirements listed in chapter 3.1. Usually, the camera's case can be taken apart and the removed PCB with the camera image sensor and the transmitter will only have a small fraction of the total camera weight including it's case. Table 3.1 lists cameras with the weight promoted by the manufacturer, including the camera's case and wall mounting. In the column $t_{S,min}$ the minimum shutter times are listed. The Power column displays the camera's power consumption, the column VGA FPS lists the maximum frames per second at VGA resolution (640x480 pixels).

Table 3.1: Selection of possible digital WiFi cameras

Camera	Price	Weight	VGA FPS	Power	$t_{S,min}$
Asante SecureNet Voyager I	120 USD	309 g	30	10 W	unk.
Vivotek IP7137	200 EUR	165 g	30	4 W	$\frac{1}{15000}\ s$
Vivotek PT7137	300 CHF	271 g	30	8 W	$\frac{1}{15000}\ s$
AXIS M1011-W	265 CHF	94 g	30	7 W	$\frac{1}{5000}\ s$

Figure 3.1: WiFi camera AXIS M1011-W
http://www.axis.com/products/cam_m1011w/index.htm,
requested: 25/6/2011

3.3 AXIS M1011-W

The decision fell on the AXIS M1011-W camera (which can be seen on figure 3.1), mainly because it is very lightweight and was available at local internet stores. The two big uncertainties were the weight of the camera's PCB after removal of the unneeded housing and weather the lens mounting allowed to insert a lens with the desired angle of view. The weight turned out to be only $25\,g$ after removal of the housing which is a great result compared to the overall weight of $94\,g$ promoted by the manufacturer. Exchanging the lens was no problem as well because the PCB of the AXIS M1011-W holds a common M12x0.5mm thread ("S-mount"). Only for heavy lenses the plastic thread feels insufficient because it is loose when the lens is put inside.

3.3.1 Lens

The lens "Lensagon BVM5015014" (see figure 3.2) was chosen to be used for the camera. The angle of view can be adjusted to a desired value between $19°$ and $41°$. With a weight of $35\,g$ the lens is heavy compared to plastic lenses ($\approx 2\,g$) but the quality is better due to better quality materials used. A detailed datasheet of the lens can be found in appendix B.1.

Figure 3.2: Lensagon BVM5015014 lens
http://www.lensation.de/de/shop.html?page=shop.product_details&product_id=172, requested: 25/6/2011

The images captured with this lens seemed to have inappropriate colours as visible in chapter 6 and appendix D. This problem was not further worked on due to lack of time but should be fixable by e.g. colour adjustments of the images after capturing.

3.3.2 Wireless connection

The communication between the camera and the ground station is 2.4 GHz WiFi. A WiFi router connected to a notebook is used as a ground station to receive the images sent from the camera. The AXIS M1011-W camera uses an unidirectional Antenova Rufa 2.4 GHz SMD Antenna of the type A5839. The radial gain distribution of the antenna in the XY, ZY and XZ planes can be seen on figure 3.3 (see appendix B.4 for more information).

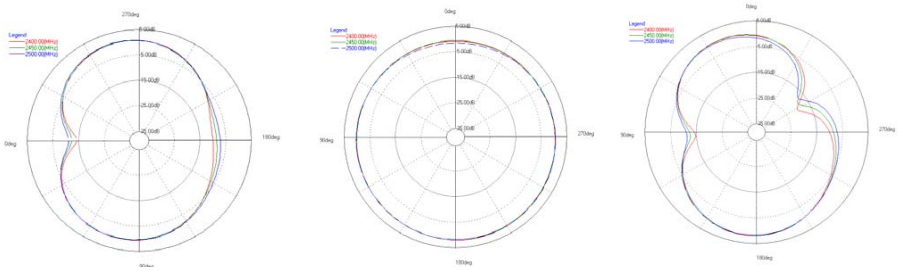


Figure 3.3: Antenova A5839 antenna: Radial gain distribution pattern in the XY, ZY and XZ planes, http://www.antenova.com/?id=744, requested: 25/6/2011

3.3.3 Board modifications

Figure 3.4 shows the top, bottom and side view of the AXIS M1011-W camera board.

Figure 3.4: WiFi camera AXIS M1011-W PCB: Top, bottom and side view

The pan/tilt angle information of the servos is currently sent to the ground station by Bluetooth (see chapter 3.4). Using the camera's wireless connec-

tion to send this information would economise the Bluetooth connection. An idea was to use the camera's audio interface to send data (the unsoldered areas are most probably reserved for audio, see appendix B.3 for other versions of the camera with audio capability). The technical section of AXIS has been contacted to ask about possibilities of modifying the AXIS camera board to achieve this but the contact to a technician has never been reached. Due to this and also due to lack of time, this idea has been dropped.

3.4 Serial data transmission

The pan/tilt angle information is sent to the ground station by Bluetooth, which is part of the Skybotix CoaX microcontroller board. The Bluetooth RX / TX should be capable of reaching a distance of up to $100\,m$. Once the servo position of the camera servos is renewed, the position is sent to the ground station by Bluetooth. For details about how this is achieved, see appendix E.8.

4 Mechanical Design

The design of the pan/tilt mounting for the camera is described in this chapter.

4.1 Requirements

The outer dimensions of the camera mounting are basically limited by the shell and the ground plate of the Paraswift robot. The length between the damping cushions of the Paraswift robot where the camera is placed in between is $20\,cm$ (see figure 4.5).

According to the design concept of the final case[1], the camera can be placed on the Paraswift robot pointing away from the shell at an angle of $\alpha = 36°$ or $\alpha = 72°$, relative to the wall. For the centre of gravity to be closer to the wall and also to reduce the force on the camera holding arm, the angle $\alpha = 36°$ has been chosen (see figure 4.1). Together with the robot's swinging angles of $\beta_1 = -68°$ and $\beta_2 = 18°$ relative to the wall during the flying phase (see chapter 2.3 for the derivation of the angle), the camera has to be able to turn $|\alpha| + |\beta_1| = 104°$ around the tilt axle, in order to keep one point in sight during the swinging of the robot. The rotation extent around the pan axle has been defined to be $180°$ so the camera can catch as much image material for a panorama as possible while the robot is on a flat wall.

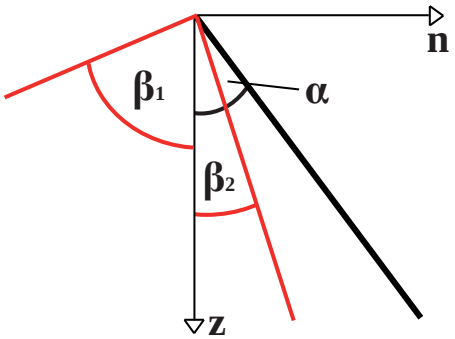


Figure 4.1: Placement of the camera on the Paraswift robot

[1] See [12] for more information about the Paraswift design concept.

4.2 Dimensions & design

At the time of the camera mounting design, the camera AXIS M1011-W itself was ordered but not yet available. This required an estimation of the camera PCB's maximum dimensions, because they were not clear at order time (see chapter 3.2). Figure 4.2 shows the outer dimensions of the chosen camera.

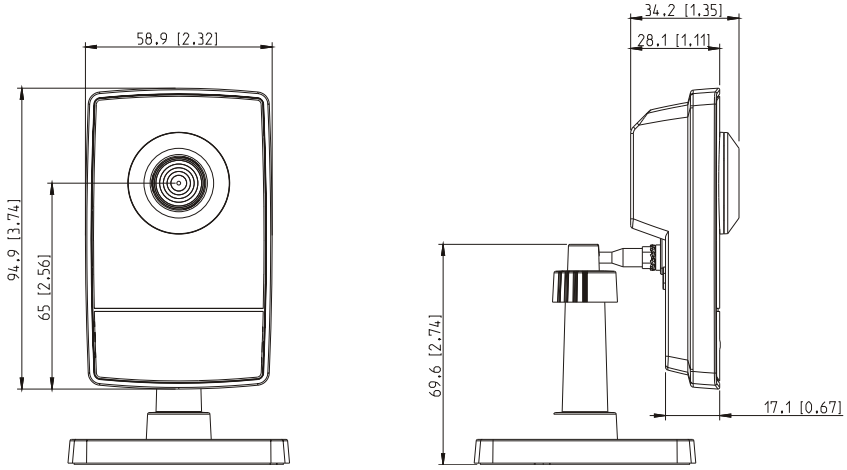


Figure 4.2: Outer dimensions of AXIS M1011-W camera
http://www.axis.com/m1011w/, requested: 13/6/2011

The camera PCB was estimated to be relatively large compared to the small image sensor on it. To rotate it on a pan/tilt mechanism requires a lot of space. Due to the latter and also due to lack of time, a mechanism has been designed in which the camera does not turn around the focal point of it's lens, which is fairly easier to design. Not turning the lens around it's focal point when capturing images can cause parallax error in the process of stitching those images together to a panorama. This error mainly occurs on short distances between the lens and recorded objects. Because this project deals with comparatively long distances to recorded objects, this parallax error was disregarded.

4.3 Material, manufacturing & weight

The camera mounting is based on lightweight parts made of bendable Peraluman aluminium and also rapid prototyping print material (characteristics similar to PVC). These materials were basically chosen because manufacturing dealings in this field were already set up within the Paraswift project.

The weight of the camera is $94\,g$ according to the manufacturer (see appendix B.2 for the camera's specifications). After removing the plastic housing of the camera, the weight of the camera PCB alone turned out to be $25\,g$. The total weight of the camera PCB and the pan/tilt mechanism reached $\approx 130\,g$. A detailed listing of all components and the corresponding weights can be viewed in table 4.1.

Table 4.1: Weight of all used components

Component	**Density**	**Weight**
AXIS M1011-W camera PCB		25 g
LENSAGON BVM5015014 lens		35 g
Servos 3x		33 g
Bracket 1	2.7 g/cm^3	9.0 g
Cam mount	1.4 g/cm^3	1.0 g
Part of rotating axis	1.4 g/cm^3	2.0 g
Carbon rod	15 g/m	2.25 g
Ball bearings 5x		2.5 g
Bearing shaft top	1.4 g/cm^3	7.9 g
Screws, glue		8 g
Servo bearing mount	1.4 g/cm^3	1.3 g
top mount part	1.4 g/cm^3	1.9 g
Servo mounting parts 12x	1.4 g/cm^3	0.32 g

4.4 Optimization & implementation

The CAD model of the camera mounting was drawn into the Paraswift concept model. The maximum outer dimensions of the camera's PCB were drawn as cross-sections because they were unclear at the time of the mounting design. Once the manufacturing of the first design (see Fig. 4.3) was done, some disadvantages became clear after the camera was received and fixed onto the mounting, which required a redesign (see Fig. 4.4). The following changes were done to the camera mounting to reach the optimized final design:

- The gearwheels were removed due to the clearance between the teeth. Instead of using gearwheels, the joint of the servo has directly been used as the turning points of the pan axle (same design as for the tilt axle). This design increases precision in the positioning of the camera.

[1] See appendix B.1 for lens specifications

- Big parts made of rapid prototyping print material have been removed from the joint section. The material turned out to be too bendable and thus was avoided to be used for parts on which a bending force is applied. Instead the aluminium bracket was extended around the bearing. This change lowered the oscillation of the camera around the pan axle by a multiple and made this effect negligible.
- The weight of the used lens of $35\,g$ turned out to generate too much side load on the plastic S-mount thread on the camera PCB, which originally carries a lens with a weight of $\approx 2\,g$. The heavier lens caused the image to be blurred in certain positions of the camera where the lens axle was not normal to the camera image sensor. Thus a lens holding arm was designed to distribute the weight of the lens to other parts of the camera's PCB.

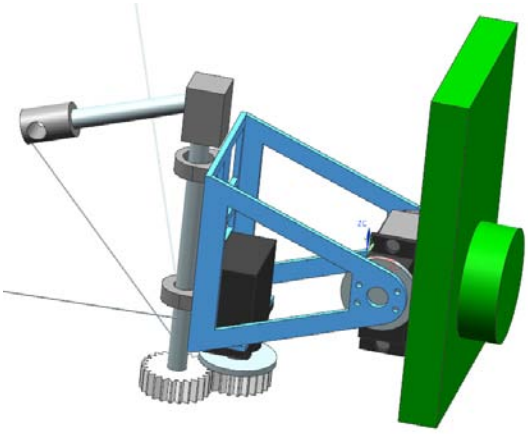


Figure 4.3: Camera mounting CAD model: Design I

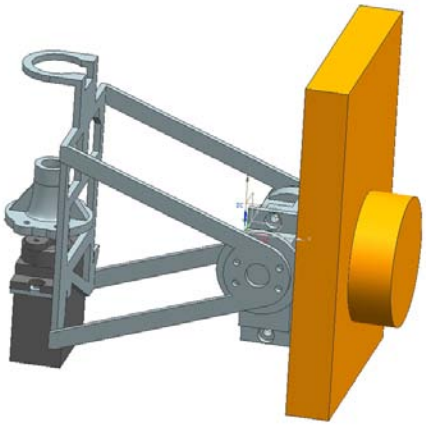


Figure 4.4: Camera mounting CAD model: Design 2

A final mechanism to swing the camera mounting into a safe area before the landing of the Paraswift robot has conceptually been designed (see figure 4.5) and has also been taken into account in table 4.1. Nevertheless the whole mechanism has not been implemented into the Paraswift robot due to lack of time. Instead, the pan/tilt mechanism was mounted on a test stand for experiments (see chapter 6).

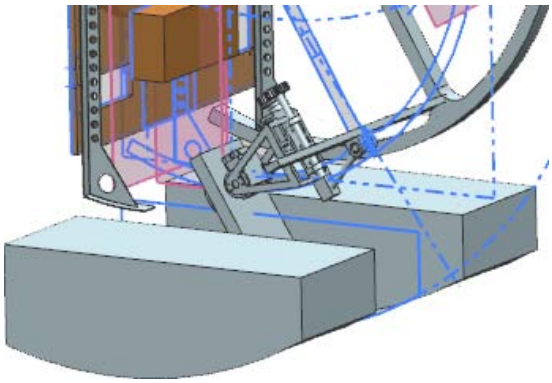


Figure 4.5: Damping cushions on the bottom of the Paraswift robot with the camera pan/tilt mechanism inbetween.

5 Computer Vision

This chapter lies a focus on the software components used to create the panoramic images out of the captured image material. The course of action was to test a few existing software components and then chose the one that fits best as the core component of panoramic image creation. The self-made part was decided to do the automated routine and call the application that creates the panorama.

5.1 Existing software

When searching the web for panorama stitcher applications, the amount of results is immense. Although only a few are easy to use and free of charge. Some of the applications introduced in chapter 1.5.1 have been installed on a MacBook with Mac OS X 10.6.6 for testing. Installation protocols can be found in appendix C. A closer look was taken on "Autostitch", "Windows Live Photo Gallery" and "PTStitcherNG". Benchmarking of these applications can be found in chapter 6.2, appendix D shows panorama images stitched with them.

5.1.1 One-click stitching

The application Autostitch[1] is available for download as a demo version. It stitches panoramas pretty fast and matches features well. As the name says, Autostitch operates automatically after choosing source images. It has a lot of optional settings for fine-tuning. In a likewise way as Autostitch, Windows Live Photo Gallery[2] also stitches panorama images with one click and is completely free of charge. Compared to Autostitch, it has no options to fine-tune the panorama creation process.
Both of these programs work by one click in the GUI and don't support command-line usage in the free versions available on the internet.

[1] More information on: `http://cvlab.epfl.ch/~brown/`
[2] More information on: `http://explore.live.com/windows-live-photo-gallery/`

5.1.2 Command-line stitching with Panorama Tools

The application PTStitcherNG[3] can be used to stitch images to panoramas along with the information in which direction the camera was pointing when taking the image. It has a lot of settings for the panorama and for every single input image. PTStitcherNG and other command-line tools like cpfind or PToptimizer are included in PanoTools[4].

Stitching images together to a panorama with PTStitcherNG works in the following way: Images are stored together with a so called project file in a folder. See appendix D.3 for an example image series along with a corresponding project file. The project file starts with the following lines:

```
p f1 w1500 h900 v360  n"tiff"
m  i0
```

Where **p** describes the output panoramic image with **f** that defines the projection mode, **w** and **h** that set the size of the output image, **v** which stands for the field of view and **n** that defines what image type should be created (jpg, tiff, ...). The **m**-line defines global options such as **i** which defines the interpolation mode. Every input image that is included in the panorama requires another line in the project file:

```
o f3 w648 h972 n"Image0.JPG" r0 p0 y0 v89.24
o f3 w648 h972 n"Image1.JPG" r0.34 p-0.31 y51.75 v89.24
o f3 w648 h972 n"Image2.JPG" r1.68 p0.94 y118.38 v89.24
...
```

Lines starting with **o** signalize an image line with **f** that sets the projection mode, **w** and **h** that set the size of the input image, **n** which defines the name of the input image and finally **r**, **p**, **y** and **v** which set roll, pan, tilt angles and the field of view of the lens. A more detailed explanation of these settings and more possible parameters can be found on [7].

PanoTools is a collection of programs to stitch images fast and in automated environments. While PTStitcherNG is used to stitch images to a panorama, cpfind can be used to find control points on images and PToptimizer can be used to optimize these control points before using PTStitcherNG for the final panorama creation. When testing PTStitcherNG, I found that it is hard to see what values are allowed for certain parameters. Fine tuning is a matter

[3] More information on: `http://webuser.hs-furtwangen.de/~{}dersch/`
[4] More information on: `http://panotools.sourceforge.net`

of trial and error because of insufficient description for the unfamiliar end user. Nevertheless PTStitcherNG has been chosen for the panorama stitching process because it is very fast[5], command-line accessible and available as freeware.

5.2 Software development: PanoProcessor

The self made part of the software used in this thesis, "PanoProcessor", is responsible for grabbing images and pan/tilt information from the Paraswift robot, modify this data and execute the required command-line applications from the PanoTools collection. It basically grabs images through the web-interface of the camera and saves the corresponding pan/tilt angles that are fetched through Bluetooth. After the grabbing process, the pan/tilt data is adjusted and fed to the command-line programs cpfind, PToptimizer and PTStitcherNG along with the captured images.

The software is written on a MacBook Pro running Mac OS X 10.6.6 and the IDE Xcode 3.2.5. All of the self-made software is written in object oriented C++ and should be transferable to a Windows or Linux platform with only little effort. The whole software source code can be obtained here:
`http://balp.paraswift.ch/PanoProcessor_v1.0_source.zip`

The following chapters roughly explain the code of Pano Processor.

5.2.1 Main routine

The whole program should be easily understandable by only looking at the file main.cpp which can be found in Appendix E.1. The file starts with the inclusion of libraries and the creation of needed subclass objects. A command-line menu is realised with a switch statement wherein the char "mode" can be set to the desired mode. The following program modes can be chosen:

- mode **g**: This is the image grabbing mode. A serial connection is set up and serial data is gathered. When a particular signal is received over serial, an image is grabbed from the camera and the corresponding pan/tilt info is saved to a text file (also see chapter 5.2.2). For the

[5] See chapter 6.3.1 for benchmarking of PTStitcherNG

grabbing mode to work, the Paraswift program on the CoaX board needs additional software (see chapter 5.2.3).

- mode **d**: The debugging mode does almost what mode "g" does, except that images are not saved, received data from serial is printed to the console and the program will stop running after 20 seconds.
- mode **p**: Entering this mode will use PTStitcherNG to create a panorama of the grabbed images only with the use of the saved pan/tilt camera angles. This is the fastest panorama creation mode (see chapter 6.3.1).
- mode **f**: This mode will use PTStitcherNG to create a panorama like mode **p**. Supplementary, also control points on images are located with cpfind and used in the panorama creation process. After entering the mode **f** it is possible to chose to compare control points only on nearby images or to compare control points from every image with every other image. The latter option obviously takes up a multiple of the time as only comparing nearby images.
- mode **s**: The "series"-mode can create an image-series illustrating the stitching process using PTStitcherNG with pan/tilt camera angles only. PTStitcherNG is executed for every image and creates a panorama of the series. Finally also a video is created using ffmpeg[6].
- mode **q**: Choosing this mode will quit the program.

After one mode of the program is executed, the menu will always prompt for the next mode to be executed until the mode **q** is chosen to exit.

5.2.2 Additional classes

To keep main.cpp clearly arranged a number of classes have been written to take over certain parts of the program. The header files of these classes can be found in appendix E. A short explanation of all classes is given below:

- **BufferManager** is responsible for the storage of data received over the serial connection. The received data can be passed to the function processInput which will look for strings in the format of: [identifier@value]. An example is: [ya@0.2] which would mean that

[6] More information on: `http://www.ffmpeg.org`

the yaw angle is at a value of 0.2. The data is saved into a data array of the type double.

- **CamHandler** can grab images from the AXIS M1011-W camera over it's web interface using the command-line program wget[7]. Images are saved to the working directory. This function should be easily modifiable to work with other cameras.
- **FileManipulator** contains functions to manipulate text files of which the most are PanoTools compatible project files. There are a few functions to convert project files from one PanoTools format to another one, e.g. convert a PTStitcherNG compatible project file to a cpfind compatible project file. Other functions go through project files line by line and adjust image lines to e.g. centre the panorama or cut images which lie out of the boundaries of the panorama which would cause errors while feeding them to PTStitcherNG.
- **SerialConnection** takes care of establishing a connection to a serial device and returning the received data. It is used within PanoProcessor to establish the connection to the Bluetooth adapter which will talk to the Skybotix CoaX microcontroller on board of the Paraswift robot.
- **Utils** contains a few minor function for data type conversion and string manipulation.
- **Settings** holds values of all the needed settings for the PanoProcessor environment. These are e.g. paths of used command-line applications, paths to used text files and settings for the camera and serial connection.

5.2.3 Microcontroller program

For PanoProcessor to work, a small piece of software has to be added to the Paraswift software on the CoaX microcontroller. A required function is "imagecapture" which has to be included above the main() function. In the main()-function, "imagecapture" can be called while rotating about the pan/tilt angles. The required code can be seen in appendix E.8.

[7] More information on: `http://www.gnu.org/software/wget/`

5.2.4 Using PanoProcessor

The following steps have to be taken to use PanoProcessor:

- Obtain the source code of PanoProcessor from:
  `http://balp.paraswift.ch/PanoProcessor_v1.0_source.zip`
- Change the file settings.h: Edit all options to fit your environment. The default options set the working directory to ~/Desktop/Capture, in which images are saved and processed.
- Compile the code with gcc or C++.
- Make sure that the CoaX board has the needed code included, which can be found in appendix E.8.

PanoProcessor can be used without the hardware connected, to process earlier captured image series. A few series of images to test PanoProcessor can be obtained from here:
`http://balp.paraswift.ch/Capture_Tests.tar.gz`

6 Experiments & Results

6.1 Captures

All capture experiments have been made with the AXIS M1011-W camera mounted on a test stand, as depicted on figure 6.1.

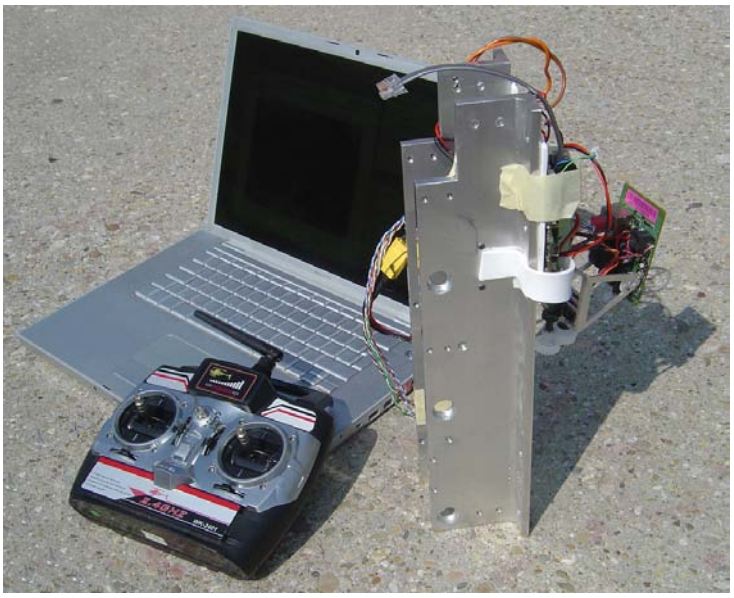


Figure 6.1: Capture equipment including camera on a test stand

Images have been collected at various locations in Zurich for stitching tests. The first captures have been made without saving the corresponding pan/tilt angle information of the camera to test one-click stitching applications. Results can be seen in appendix D.1 and D.2. When comparing figures D.1 and D.2 or figures D.3 and D.4 with each other, it can be seen that certain parts of the images are stitched differently.

6.2 PTStitcherNG test images

The program PTStitcherNG contains a series of 7 images together with a project file to test the stitching process. The images and the project file can

be found in appendix D.3. These images have been stitched with PTStitcherNG, Autostitch and Windows Live Photo Gallery. Resulting panoramic images can be seen in appendix D.3.

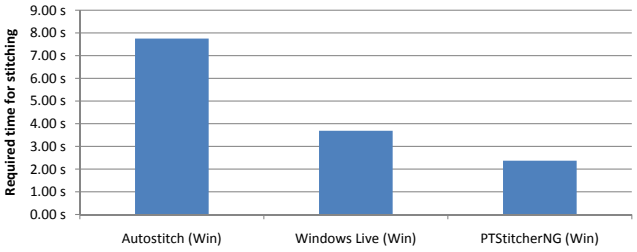


Figure 6.2: Stitching with and without position information

Comparing the required stitching time for this image series of one-click stitching applications and PTStitcherNG (see figure 6.2) it can be seen that PTStitcherNG is the fastest. The difference of the required stitching time from one-click stitchers compared to PTStitcherNG should increase non linear by an increasing number of images because one-click applications normally compare all images with all other images (see chapter 1.5.3 for details).

6.3 Stitching with PTStitcherNG

To get used to the input parameters of PTStitcherNG, the project file of the PTStitcherNG testing image series has been taken as a basic for a series of images captured with the camera on the test stand. The images have been aligned by setting the corresponding pan/tilt angles manually (trial and error). The result can be seen on figure D.9 of appendix D.4. After this manual alignment, the pan/tilt angles of the capture have been converted with PanoProcessor (see chapter 5.2) to look about as with the manual alignment (see figure D.10 of appendix D.4). This result is imperfect because of parallax error (small scene distance) and an unoptimized pan/tilt mechanism. After optimizing the mechanical part of the mechanism (see chapter 4.4) the resulting panoramic images generated only by the use of the pan/tilt angle information looked quite better (see figure 6.3). Further optimization was done to the software part by including comparison of control points of nearby images which improved the resulting images again (see figure 6.4).

Figure 6.4 shows panoramas generated by the use of pan/tilt information and by comparing control points on nearby images. (The same panoramas

Figure 6.3: Panoramas stitched by PTStitcherNG by the use of pan/tilt angle information only

Figure 6.4: Panoramas stitched by PTStitcherNG by using pan/tilt angle information and by comparing control point of nearby images

stitched by only pan/tilt angle information are visible on figure 6.3.) It can be seen that even by using control point matching on nearby images the stitching is not yet perfect. Further optimization that could be done to the panorama creation process is discussed in chapter 7.

6.3.1 Required stitching time

The most important result of stitching images with PTStitcherNG by providing pan/tilt angle information of the camera for every image is the short stitching time compared to one-click automatic stitching applications. Figure 6.5 shows an example of the required stitching time for an image series of 267 images, each with a resolution of 640x480 pixels. These measure-

ments have been done on a regular desktop PC. Stitching such an image series with PTStitcherNG only by considering pan/tilt angle information, the required time was always $< 10\,s$. The time for stitching with PTStitcherNG and also comparing control points of nearby images was always: $1\,min < t < 2\,min$. When stitching the same series with Autostitch, the required time was around $10\,min$.

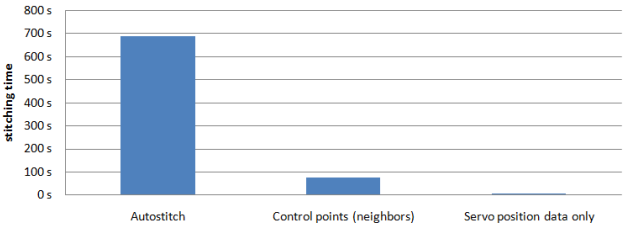


Figure 6.5: Required time for stitching an image series with Autostitch and PTStitcherNG (considering nearby control points and servo position data only)

The panoramic images of the specific example illustrated in figure 6.5 can be seen on figure 6.6. The required times for stitching are as follows:

- Autostitch (comparing control points from all images with all images): **689.5 s** (11.5 min)
- PTStitcherNG (comparing control points on neighbour images): **78.0 s** (1.3 min)
- PTStitcherNG (only using pan/tilt angle information): **5.3 s** (0.1 min)

It must be said that Autostitch and also PTStitcherNG use random algorithms like RANSAC[1]. Therefore the required time for generating a panoramic image out of the same image series can vary by around 10 %.

6.3.2 Ceiling

A big advantage from having the pan/tilt angle information available compared to for example one-click stitching applications is that if the recorded images have low textures, they will still be placed according to their pan/tilt information. Examples for this are images with a big amount of ceiling with no clouds. Applications only using control points sometimes can't detect any of these points in the ceiling which makes them unable to stitch such a panorama well.

[1] More information on: `http://en.wikipedia.org/wiki/RANSAC`

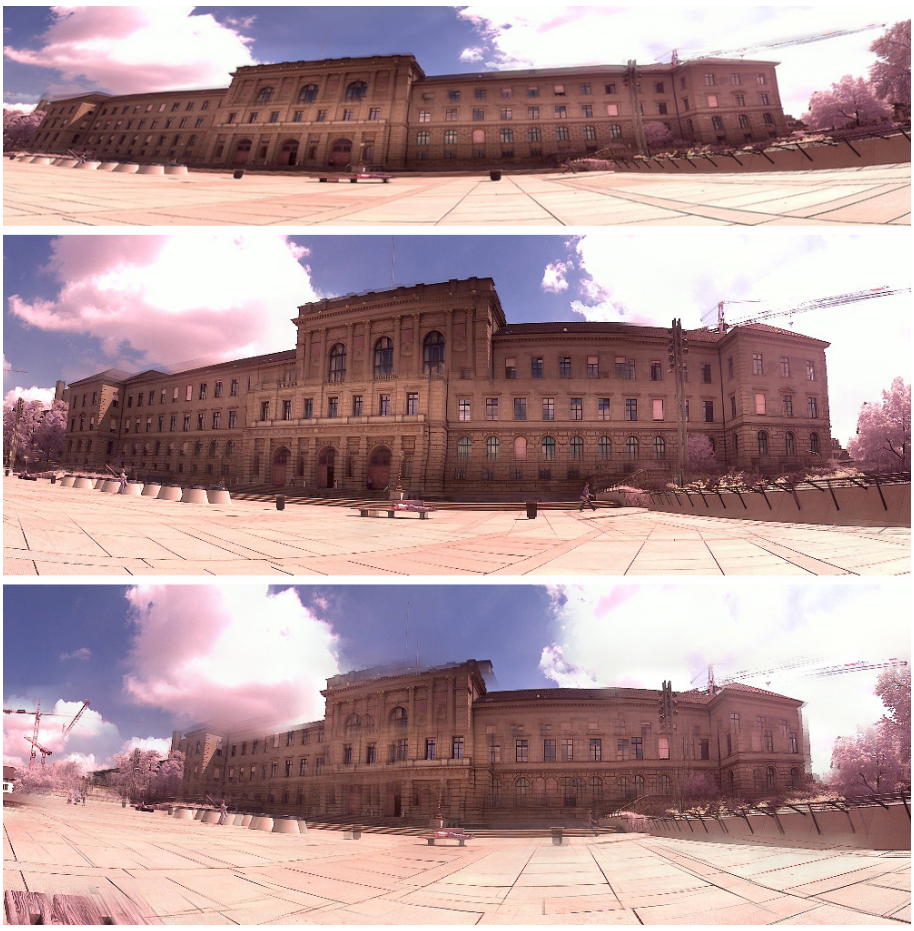


Figure 6.6: Stitching of 267 images with Autostitch (top), PTStitcherNG by comparing control points on neighbour images (middle) and with PTStitcherNG only by using pan/tilt angle information (bottom)

7 Conclusion & Outlook

The output of this thesis is very satisfying. An easy to use application has been produced, which creates good looking panoramic images in a very competitive time. The fastest panorama creation with the developed PanoProcessor software is even ten times faster than with a common application even though the final panorama is not flawless, but still nice to look at. All the "must-have"-goals have been reached with good results. The "nice-to-have"-goals were not reached due to lack of time and maybe they have been set while being overconfident. Conceptually the flying phase of the Paraswift robot has been looked at but the implementation into the robot and also experiments using the Paraswift wall climbing and base jumping system never happened. Instead at least an analogue camera with a wide screen lens was mounted on the robot at a Paraswift show to get at least some expertise of the flying phase.

Working with PanoTools and especially PTStitcherNG was not always easy. The lack of documentation required a trial and error approach to find out how these programs work. Nevertheless it must be said that the PanoTools newsgroups were a good drop-in centre to receive support. In return the PanoTools applications are available as freeware and seem to be the only existing command-line panorama environment that is freeware.

Finally, working on this thesis was mostly very diversified because it is a multidisciplinary thesis in which mechanics, electronics, optics and software development are united. It was a challenge to overlook all the different parts and not invest too much time into one thing while disregarding something else.

Due to the fact that this thesis only makes use of freeware applications, it can easily be distributed to other people to work on it and do further research with the output of this thesis as a starting point.

Below is a list of possible improvements to the hard- and software part of this thesis:

- Currently the servos of the pan/tilt joints are controlled by the CoaX microcontroller. They are set to a desired position (no feedback), which is also the position used to send to the laptop ground station as pan/tilt angles for the corresponding captured image. By adding encoders or potentiometers to the joints and connecting them to the microcontroller, the positioning error could be minimized which would result in a much better panorama image that is created only by the information of the pan/tilt angles.
- By turning the pan/tilt camera mounting around the focal point of the camera lens, the parallax error could be removed. This would allow for indoor capture, as the distance to the scene could be very small. This has not been done because it was not necessary for the used scene distance of $> 15\,m$.
- Other applications than PanoTools could be used for the same purpose, like e.g. Autostitch MATLAB version which supports usage in a programmable / scripting environment (conditions of usage would have to be clarified because it is not freeware).
- Looking at the flying phase of the robot would be a nice addition to have more possibilities during the Paraswift show. Using the camera while flying for the localization of the current height by comparing the view with previously generated panoramas (panoramas generated while being in climbing mode) is an example.

When slightly changed, the ideas and software code of this thesis could also be used in different fields than entertainment like e.g. video surveillance or inspection robotics. In video surveillance it is important to have good quality image material to recognize happenings on the recorded image/video material for a specific area of the image but at the same time it is helpful to see the whole image. By using the pan/tilt mounted camera, only important scene details could be updated while still having a wide screen overview of the rest of the image. Also inspection robotics need to see details while for the person controlling the inspection robot it is good to have an overall view as well. The previously recorded material could be stored and added to the overall view while details would get updated continuously.

8 Directories

8.1 List of abbreviations

ASL	Autonomous Systems Lab
DRZ	Cathode ray tube
DRZ	Disney Research Zurich
ETHZ	Federal Institute of Technology Zurich
FPS	Frames per second
FPV	First Person View
GUI	Graphical user interface
IDE	Integrated development environment
IR	Infrared
LCD	Liquid crystal display
OOP	Object-oriented programming
PCB	Printed circuit board
PVC	Polyvinyl chloride (thermoplastic polymer)
RANSAC	Random Sample Consensus
RC	Radio Controlled
TFT	Thin-film transistor
VGA	Video Graphics Array

8.2 Bibliography

[1] *Handbuch der Bildverarbeitung*. Stemmer Imaging, 2010.

[2] http://en.wikipedia.org/wiki/Exposure_(photography), requested: 04/06/2011.

[3] http://en.wikipedia.org/wiki/Motion_blur, requested: 04/06/2011.

[4] http://en.wikipedia.org/wiki/Shutter_(photography), requested: 04/06/2011.

[5] http://en.wikipedia.org/wiki/Angle_of_view, requested: 04/26/2011.

[6] http://en.wikipedia.org/wiki/Rolling_shutter, requested: 05/06/2011.

[7] http://webuser.hs-furtwangen.de/ dersch/, requested: 06/06/2011.

[8] http://en.wikipedia.org/wiki/Interlaced_video, requested: 23/04/2011.

[9] http://www.axis.com/products/video/camera/progressive_scan.htm, requested: 23/04/2011.

[10] E. Altug, J.P. Ostrowski, and C.J. Taylor. Control of a quadrotor helicopter using dual camera visual feedback. *The International Journal of Robotics Research*, 24(5):329, 2005.

[11] T. Kanade, O. Amidi, and Q. Ke. Real-time and 3d vision for autonomous small and micro air vehicles. In *Decision and Control, 2004. CDC. 43rd IEEE Conference on*, volume 2, pages 1655–1662. IEEE, 2004.

[12] Team Paraswift. World's first base jumping robot, 2011.

[13] 360 precision. *Precision Panoramic Heads*, may 2011. `http://www.360precision.com`.

[14] ME Rentschler, J. Dumpert, SR Platt, SI Ahmed, SM Farritor, and D. Oleynikov. Mobile in vivo camera robots provide sole visual feedback for abdominal exploration and cholecystectomy. *Surgical endoscopy*, 20(1):135–138, 2006.

[15] Q. Shan, J. Jia, and A. Agarwala. High-quality motion deblurring from a single image. In *ACM SIGGRAPH 2008 papers*, pages 1–10. ACM, 2008.

8.3 List of figures

1.1 Illustration of Paraswift show by Maurizio Nitti, DRZ . . . 11
1.2 Paraswift show, 21. June 2011 at ETH Zurich 11
1.3 Paraswift robot system overview 12
1.4 Work breakdown structure of the thesis 13
1.5 Example image with motion blur [3] 15
1.6 Example image showing the effect of rolling shutter [6] . . 15
1.7 Example image (interlaced) [9] 15
1.8 Example image (progressive scan) [9] 15
1.9 Control point comparison illustration from Autopano Pro GUI http://www.kolor.com/panorama-software-autopano-pro-interface.html, requested: 25/06/2011 16

2.1 Example portrait with 22 pixels "face resolution". 19
2.2 Geometrical calculation of the angle of view. 20
2.3 Amount images to be captured (a) horizontally and (b) vertically 21
2.4 Swinging angle of the down flying Paraswift robot around the tilt/pitch axle 22

3.1 WiFi camera AXIS M1011-W http://www.axis.com/products/cam_m1011w/index.htm, requested: 25/6/2011 26
3.2 Lensagon BVM5015014 lens http://www.lensation.de/de/shop.html?page=shop.product_details&product_id=172, requested: 25/6/2011 27
3.3 Antenova A5839 antenna: Radial gain distribution pattern in the XY, ZY and XZ planes, http://www.antenova.com/?id=744, requested: 25/6/2011 28
3.4 WiFi camera AXIS M1011-W PCB: Top, bottom and side view 28

4.1 Placement of the camera on the Paraswift robot 31

4.2 Outer dimensions of AXIS M1011-W camera http://www.axis.com/m1011w/, requested: 13/6/2011 . . 32
4.3 Camera mounting CAD model: Design I 34
4.4 Camera mounting CAD model: Design 2 34
4.5 Damping cushions on the bottom of the Paraswift robot with the camera pan/tilt mechanism inbetween. 35

6.1 Capture equipment including camera on a test stand 43
6.2 Stitching with and without position information 44
6.3 Panoramas stitched by PTStitcherNG by the use of pan/tilt angle information only 45
6.4 Panoramas stitched by PTStitcherNG by using pan/tilt angle information and by comparing control point of nearby images 46
6.5 Required time for stitching an image series with Autostitch and PTStitcherNG (considering nearby control points and servo position data only) 47
6.6 Stitching of 267 images with Autostitch (top), PTStitcherNG by comparing control points on neighbour images (middle) and with PTStitcherNG only by using pan/tilt angle information (bottom) 48

A.1 Time schedule 57
A.2 Roll, pitch and yaw axes used in flight dynamics http://en.wikipedia.org/wiki/Flight_dynamics, requested: 5/06/2011 58

D.1 Panorama 20110428_1 stitched with Autostitch 67
D.2 Panorama 20110428_1 stitched with Windows Live 67
D.3 Panorama 20110428_2 stitched with Autostitch 68
D.4 Panorama 20110428_2 stitched with Windows Live 68
D.5 Test image series from PTStitcherNG 69
D.6 PTStitcherNG test images stitched with PTStitcherNG . . 70
D.7 PTStitcherNG test images stitched with Windows Live . . 70
D.8 PTStitcherNG test images stitched with Autostitch 70
D.9 Stitched with PTStitcher, aligning the images manually by finding out correct pan/tilt angles for every image . . . 71
D.10 Stitched with PTStitcher, using pan/tilt information coming from the microcontroller 71

9 Appendix

A Lists, tables and illustrations

A.1 Time schedule

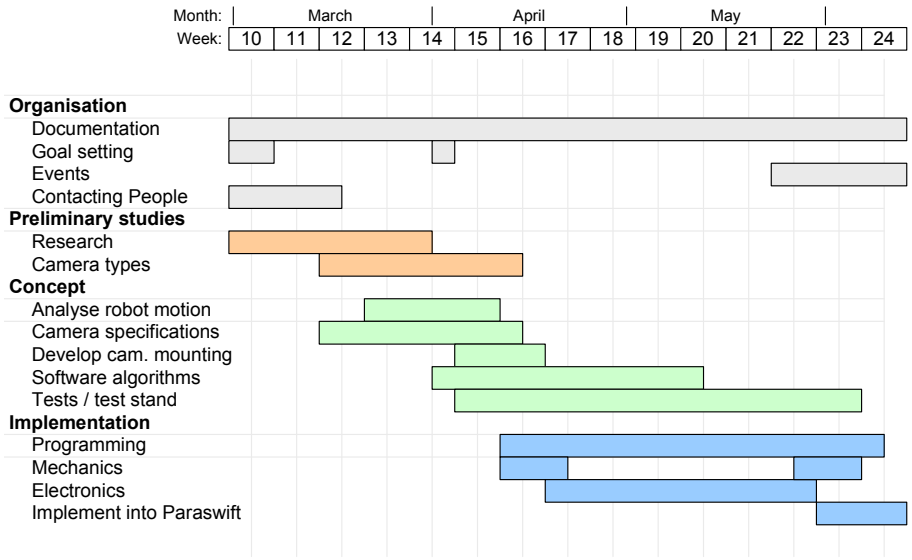


Figure A.1: Time schedule

A.2 Flight dynamics

The following image shows descriptions of the axles used in flight dynamics:

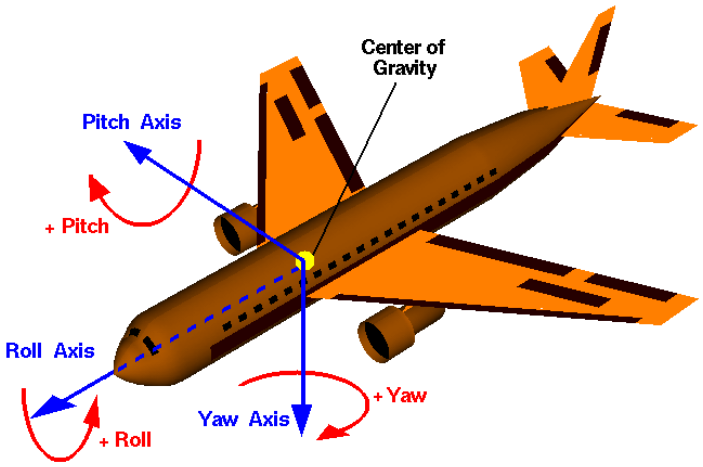


Figure A.2: Roll, pitch and yaw axes used in flight dynamics
http://en.wikipedia.org/wiki/Flight_dynamics, requested: 5/06/2011

For camera systems, the axle descriptions **pan** and **tilt** are often used where pan refers to **yaw** and tilt to **pitch**.

B Data sheets, technical specifications

B.1 LENSAGON BVM5015014 lens

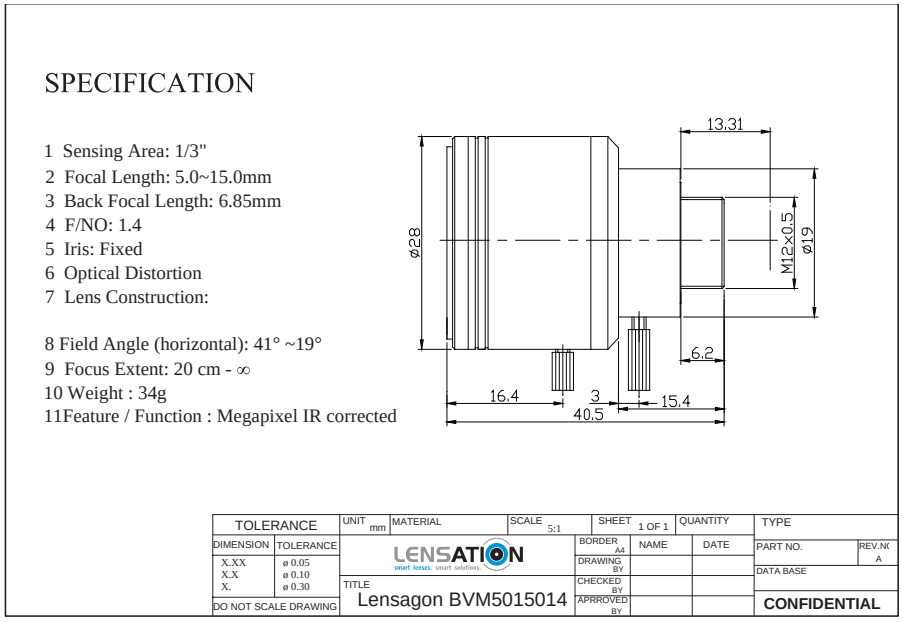


Table B.1: BVM5015014 lens specifications from www.lensation.de, 18.06.2011

Image format	1/3 inch
Mount type	S-Mount (M12x0.5)
Megapixel	1 MP
Vari-focal	Yes
Focal length (max)	5 mm (15 mm)
Back focal length	6.85 mm
Aperture (F)	1.4
M.O.D.	0.2 m
Angle of View (diag.)	41 °
Angle of View (diag. max.)	19 mm
Zoom	manual with lock
Focus	manual with lock
Iris	fixed
Weight	35 g

B.2 AXIS M1011-W camera

www.axis.com

Technical Specifications – AXIS M10 Network Camera Series

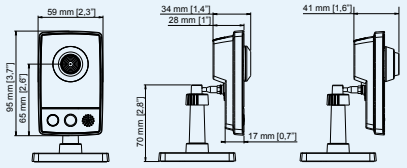
Camera	
Models	**AXIS M1011:** Wired interface **AXIS M1011-W**: Wired and wireless interface **AXIS M1031-W**: Wired and wireless interface, PIR sensor, illumination LED, audio **AXIS M1054**: Power over Ethernet, PIR sensor, illumination LED, audio, I/O ports
Image sensor	**AXIS M1011/M1011-W/M1031-W**: 1/4" progressive scan RGB CMOS, **AXIS M1054**: 1/4" progressive scan RGB CMOS
Lens	**AXIS M1011/M1011-W/M1031-W**: 4.4 mm: 47° view*, F2.0, fixed iris, fixed focus **AXIS M1054**: 2.9 mm: 84° view*, F2.0, fixed iris, fixed focus *horizontal angle of view
Light sensitivity	**AXIS M1011/M1011-W/M1031-W**: 1-10000 lux, F2.0 **AXIS M1054**: 1.2 - 100000 lux, F2.0 **AXIS M1031-W/M1054**: 0 lux with illumination LED on
Shutter time	**AXIS M1011/M1011-W/M1031-W**: 1/5000 s to 1/4 s **AXIS M1054**: 1/24500 s to 1/6 s
Pan/Tilt/Zoom	**AXIS M1054**: Digital PTZ, preset positions, guard tour
Video	
Video compression	H.264 (MPEG-4 Part 10/AVC), Motion JPEG **AXIS M1011/M1011-W/M1031-W**: MPEG-4 Part 2 (ISO/IEC 14496-2)
Resolutions	**AXIS M1011/M1011-W/M1031-W**: 640x480 to 160x120 **AXIS M1054**: 1280x800 to 160x90
Frame rate	**H.264**: 30 fps in all resolutions **Motion JPEG**: 30 fps in all resolutions **AXIS M1011/M1011-W/M1031-W, MPEG-4 Part 2**: 30 fps in all resolutions
Video streaming	Multiple, individually configurable streams in H.264 and Motion JPEG, as well as MPEG-4 Part 2 with AXIS M1011/ M1011-W/M1031-W Controllable frame rate and bandwidth VBR/CBR H.264, MPEG-4 Part 2
Image settings	Compression, color, brightness, sharpness, contrast, white balance, exposure control, exposure zones, backlight compensation, fine tuning of behavior at low light, rotation Text and image overlay, Privacy mask **AXIS M1054**: Mirroring
Audio (AXIS M1031-W & AXIS M1054)	
Audio streaming	Two-way
Audio compression	AAC-LC 8/16 kHz, G.711 PCM 8kHz, G.726 ADPCM 8 kHz Configurable bit rate
Audio in/out	Built-in microphone and speaker
Network	
Wireless interface	**AXIS M1011-W/M1031-W:** IEEE 802.11g/b Invisibly integrated antenna
Security	Password protection, IP address filtering, HTTPS** encryption, digest authentication, user access log **AXIS M1011-W/M1031-W**: WEP 64/128 bit, WPA/WPA2-PSK
Supported protocols	IPv4/v6, HTTP, HTTPS**, QoS Layer 3 DiffServ, FTP, SMTP, Bonjour, UPnP, SNMPv1/v2c/v3(MIB-II), DNS, DynDNS, NTP, RTSP, RTP, TCP, UDP, IGMP, RTCP, ICMP, DHCP, ARP, SOCKS

System integration	
Application Programming Interface	Open API for software integration, including the ONVIF specification available at www.onvif.org, as well as VAPIX® from Axis Communications, specifications available at www.axis.com Support for AXIS Video Hosting System (AVHS) with One-Click Camera connection
Intelligent video	Video motion detection, active tampering alarm **AXIS M1031-W/M1054**: Audio detection
Alarm triggers	Intelligent video **AXIS M1031-W/M1054**: PIR sensor **AXIS M1054**: PIR sensor, external input
Alarm events	File upload via FTP, HTTP and email Notification via email, HTTP and TCP **AXIS M1031-W/M1054**: Activation of illumination LED, audio clip playback, **AXIS M1054**: external output activation
Video buffer	**AXIS M1011/M1011-W/M1031-W**: 16 MB pre- and post alarm **AXIS M1054**: 25 MB pre- and post alarm
General	
Processor and memory	**AXIS M1011/M1011-W/M1031-W**: ARTPEC-B, 64 MB RAM, 32 MB Flash, **AXIS M1054**: ARTPEC-3, 128 MB RAM, 128 MB Flash
Power	4.9 – 5.1 V DC, max. 6.5 W **AXIS M1054**: Power over Ethernet IEEE 802.3af Class 2 (max. 6.49W)
Connectors	DC jack, RJ-45 10BASE-T/100BASE-TX **AXIS M1054**: 1 alarm input and 1 output
PIR sensor	**AXIS M1031-W/M1054**: Passive infrared (PIR) motion sensor with configurable sensitivity. Max range: 6 m
Illumination LED	**AXIS M1031-W/M1054**: White illumination LED: 1 W
Operating conditions	Humidity 20 - 80% RH (non-condensing) **AXIS M1011/M1011-W/M1031-W**: 0 – 50 °C (32 – 122 °F) **AXIS M1054**: 0 – 40 °C (32 – 113 °F)
Approvals	**AXIS M1011:** EN 55022 Class B, EN 55024, EN 61000-3-2, EN 61000-3-3, EN 60950-1, FCC Part 15 Subpart B Class B, VCCI Class B, ICES-003 Class B, C-tick **AXIS M1011-W/M1031-W**: EN301489-1, EN301489-17, EN300328, EN 60950-1, FCC Part 15 Subpart B and C Class B, RSS-210, C-TICK, TELEC, KCC, SRRC **AXIS M1054:** EN 55022 Class B, EN 61000-3-2, EN 61000-3-3, EN 55024, FCC Part 15 Subpart B Class B, ICES-003 Class B, VCCI Class B, C-tick AS/NZS CISPR 22, KCC Class B, EN 60950-1 Power supply: EN 60950-1, cCSAus
Weight	**AXIS M1011**: 94 g (0.21 lb), **AXIS M1011-W**: 94 g (0.21 lb) **AXIS M1031-W**: 100 g (0.22 lb), **AXIS M1054**: 160 g (0.35 lb)
Included accessories	Power supply, stand and clamp, Installation Guide, CD with installation tools, recording software and User's Manual, Windows decoder 1-user license **AXIS M1054**: Extension for stand: 100 mm [4.0"]
Video management software (not incl.)	AXIS Camera Station - Video management software for viewing and recording up to 50 cameras. For more software application via partners, see www.axis.com/products/video/software/

***This product includes software developed by the OpenSSL Project for use in the OpenSSL Toolkit. (www.openssl.org)*

More information is available at www.axis.com

Dimensions



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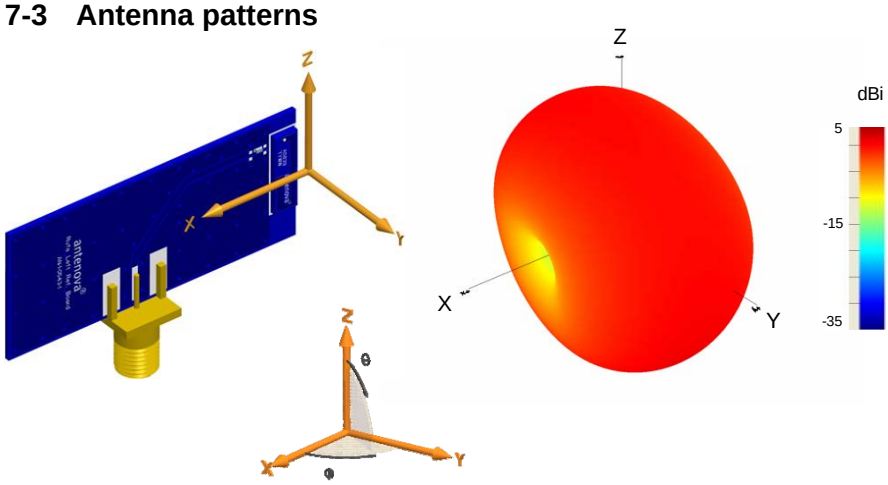
B.3 AXIS M10 camera series comparison

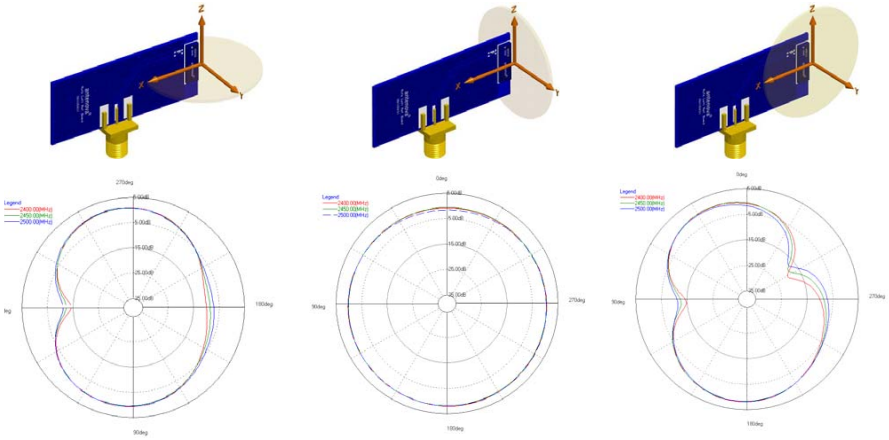
AXIS M10 Series				
	AXIS M1011	**AXIS M1011-W**	**AXIS M1031-W**	**AXIS M1054**
Image sensor	1/4" progressive scan CMOS	1/4" progressive scan CMOS	1/4" progressive scan CMOS	1/4" progressive scan CMOS
Lens	4.4 mm/F2.0 fixed iris	4.4 mm/F2.0 fixed iris	4.4 mm/F2.0 fixed iris	2.9 mm/F2.0 fixed iris
Horizontal angle of view	47°	47°	47°	80°
Day and night				
Min illumination/ light sensitivity (lux)	1 - 10,000	1 - 10,000	1 - 10,000 0 with LED on	1.2 - 100,000 0 with LED on
Video compression	H.264 Motion JPEG MPEG-4	H.264 Motion JPEG MPEG-4	H.264 Motion JPEG MPEG-4	H.264 Motion JPEG
Max video resolution (pixels)	640 x 480	640 x 480	640 x 480	1280 x 800 (1 MP)
Frames per second	30 (640x480)	30 (640x480)	30 (640x480)	30 (1280x800) 30 (HDTV 720p)
Audio support			Two-way Built-in mic and speaker	Two-way Built-in mic and speaker
Alarm in-/outputs				1/1
Intelligent video	Motion detection Tampering alarm	Motion detection Tampering alarm	Motion detection Audio detection Tampering alarm	Motion detection Audio detection Tampering alarm
Security	Multi-level passwords IP filtering HTTPS encryption	Multi-level passwords IP filtering HTTPS encryption	Multi-level passwords IP filtering HTTPS encryption	Multi-level passwords IP filtering HTTPS encryption
Network	IPv4/v6, QoS	IPv4/v6, QoS	IPv4/v6, QoS	IPv4/v6, QoS
Power	DC PoE splitter available	DC PoE splitter available	DC PoE splitter available	DC PoE IEEE 802.3af Class 2
Serial connectors				
Outdoor use				
Other	AVHS[1], ONVIF	Wireless, AVHS[1], ONVIF	Built-in PIR sensor, illumination LED, wireless, AVHS[1], ONVIF	Built-in PIR sensor, illumination LED, digital PTZ, AVHS[1], Corridor Format™

B.4 Antenova Rufa 2.4 Ghz antenna A5839

Rufa 2.4 GHz SMD Antenna
Part No. A5839 / A5887

7-3 Antenna patterns





XY plane ZY plane XZ plane

Patterns show combined polarisations measured on reference board A5839-U1

C Software installation

The following chapters list protocols of software installations which I needed for this thesis. The installations have been done on a MacBook Pro (Intel) using Mac OS X 10.6.6.

C.1 MacPorts

To install MacPorts on Mac OS X, the latest installation image (.dmg) was fetched from `http://www.macports.org` and installed using defaults. MacPorts is needed for most of the following software installations. This command updates MacPorts to the latest version:

```
sudo port selfupdate
sudo port -d sync
```

To install MacPorts from source:

```
sudo port install cmake
sudo port install boost tiff jpeg libpng wxWidgets subversion
     openexr exiv2 glew mercurial tclap
```

C.2 OpenCV

Instructions using the console (bash):

```
sudo port install subversion
sudo port install cmake
cd /opt
svn co https://code.ros.org/svn/opencv/trunk/opencv -r 3059;
    cd opencv
sudo cmake -G "Unix␣Makefiles"
sudo make -j8
sudo make install
```

Installation instructions were taken from: `http://opencv.willowgarage.com/wiki/Mac_OS_X_OpenCV_Port` (requested: 20.04.2011). The link above also contains instructions about how to create a project in xCode with openCV.

C.3 Panotools / Libpano

Instructions using the console (bash):

```
cd /opt
svn co https://panotools.svn.sourceforge.net/svnroot/
    panotools panotools
cd panotools/trunk/libpano
vi bootstrap
```

change

```
LIBTOOLIZE=${LIBTOOLIZE:-libtoolize}
```

to

```
LIBTOOLIZE=${LIBTOOLIZE:-glibtoolize}
```

```
export CFLAGS="-arch␣i386␣-I/opt/local/include␣-L/opt/local/
    lib"
export CXXFLAGS="-arch␣i386␣-I/opt/local/include␣-L/opt/local
    /lib"
./bootstrap --without-java
make
sudo make install
```

Installation instructions were taken from: `http://wiki.panotools.org/Autopano-sift-C_Compiling_OSX` (requested: 26.04.2011) and `http://wiki.panotools.org/Hugin_Compiling_OSX` (requested: 26.04.2011)

C.4 Hugin

Hugin was installed from dmg-image (fetched from `http://hugin.sourceforge.net`). In a second step, I tried to install Hugin from source, to get to know what happens "behind the scene". PanoTools is required for the installation of Hugin (see Appendix C.3).

```
cd /opt/
hg clone http://hugin.hg.sourceforge.net:8000/hgroot/hugin/
    hugin hugin
mkdir hugin_build; cd hugin_build
export CFLAGS="-arch␣i386␣-I/opt/local/include␣-L/opt/local/
    lib"
export CXXFLAGS=$CFLAGS
cmake ../hugin
make
sudo make install
```

Unfortunately, installation failed with the following error(s) and I did not go on with it due to lack of time:

```
ld: in /opt/local/lib/libsasl2.2.dylib, file was built for
    unsupported file format which is not the architecture
    being linked (i386)
collect2: ld returned 1 exit status
make[2]: *** [src/hugin_base/libhuginbase.0.0.dylib] Error 1
make[1]: *** [src/hugin_base/CMakeFiles/huginbase.dir/all]
    Error 2
make: *** [all] Error 2
```

Installation instructions were taken from: `http://wiki.panotools.org/Hugin_Compiling_OSX` (requested: 26.04.2011).

D Panoramas

D.1 Capture 201104281_1

Figure D.1: Panorama 20110428_1 stitched with Autostitch

Figure D.2: Panorama 20110428_1 stitched with Windows Live

D.2 Capture 201104281_2

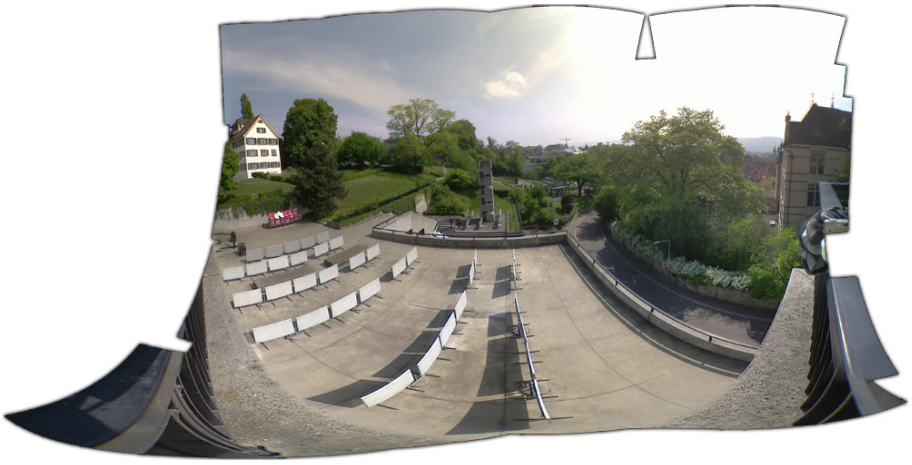


Figure D.3: Panorama 20110428_2 stitched with Autostitch

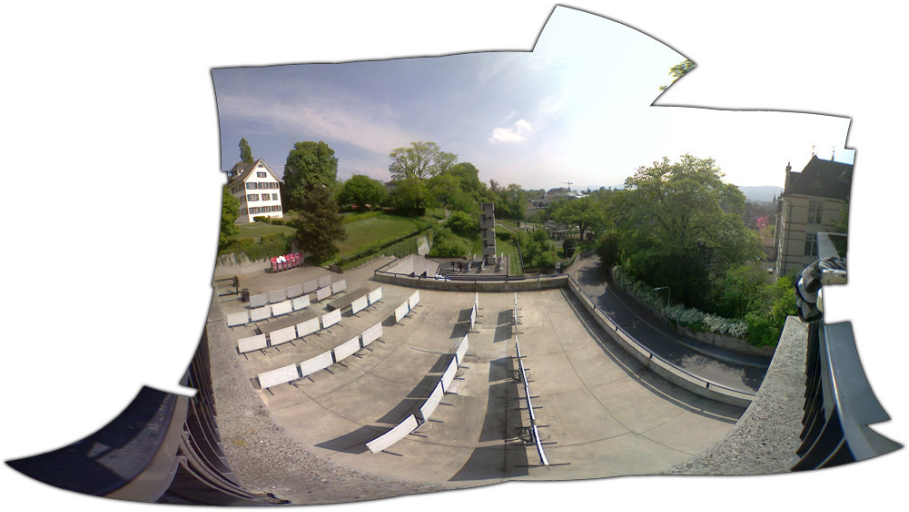


Figure D.4: Panorama 20110428_2 stitched with Windows Live

D.3 PTStitcherNG testimages

The image series included in PTStitcherNG is shown in Fig. D.5.

Figure D.5: Test image series from PTStitcherNG

The included project file can be broken down to the following minimal file:

```
p f1 w1500 h900 v360 n"tiff"
m i0
o f3 w648 h972 n"Image0.JPG" r0 p0 y0 v89.24
o f3 w648 h972 n"Image1.JPG" r0.34 p-0.31 y51.75 v89.24
o f3 w648 h972 n"Image2.JPG" r1.68 p0.94 y118.38 v89.24
o f3 w648 h972 n"Image3.JPG" r1.52 p-1.69 y-177 v89.24
o f3 w648 h972 n"Image4.JPG" r-0.48 p-1.7 y-124.67 v89.24
o f3 w648 h972 n"Image5.JPG" r-0.57 p1.51 y-47.92 v89.24
o f3 w972 h648 n"Image6.JPG" r-99.77 p85.92 y-66.3 v133.32
```

The PTStitcherNG test images were stitched with different applications in Fig. D.6, D.7 and D.8

Figure D.6: PTStitcherNG test images stitched with PTStitcherNG

Figure D.7: PTStitcherNG test images stitched with Windows Live

Figure D.8: PTStitcherNG test images stitched with Autostitch

D.4 Capture 20110513

Figure D.9: Stitched with PTStitcher, aligning the images manually by finding out correct pan/tilt angles for every image

Figure D.10: Stitched with PTStitcher, using pan/tilt information coming from the microcontroller

E Source Code

E.1 main.cpp

```
/*  main.cpp - PanoProcessor
 *  Created by Lukas Pfirter on 10.05.11. */
//  http://www.openframeworks.cc/setup/xcode
//  http://openmtproject.sourceforge.net/doc/mtview/classof_serial.html
//  http://en.wikibooks.org/wiki/Serial_Programming/termios
using namespace std;

#include <stdio.h>
#include <string.h>
#include <fcntl.h>
#include <sys/ioctl.h> // For FIONREAD
#include <stdlib.h>
#include <iostream>
#include <fstream>
#include <sys/types.h>
#include <fstream>
#include <string>
#include <sstream>
#include <sys/time.h>
#include <cstdio>
#include <iostream>

#include "BufferManager.h"
#include "CamHandler.h"
#include "SerialConnection.h"
#include "FileManipulator.h"
#include "Utils.h"
#include "Settings.h"
//#include "gnuplot_i.h" // Just for some testing, unused

int main(int argc,char** argv) {

    char mode;

    // Loop through menue until q is pressed
    while(mode != 'q') {
        double positionValues[4];   // Stores position values before save
            images

        BufferManager mybuf; // Buffer manager
        //SerialConnection myserial(Settings::getSetting("serial")); //
            Set Serial adapter
        SerialConnection myserial(Settings::getSetting("serial_bluetooth"
            ));  // Set Bluetooth adapter
        CamHandler mycam(Settings::getSetting("camera_ip_eth"),Settings::
            getSetting("folder_workdir"),Settings::getSetting("path_wget"
            ),Settings::getSetting("camera_user"),Settings::getSetting
            ("camera_password")); // Set camera IP
        FileManipulator myfilemanip(-60,60,-25,25); // Set borders for
            pitch and yaw values

        int counter = 0;    // Counter to count seconds in debug mode
        char c;             // set read to non-blocking
        int n,tem,cnt = 0;  // "


        cout << "Please chose the program mode:\n";

        cout << "  d (Debug mode; echo received serial data on console)\
            n";
        cout << "  g (Grab images and pos info from cam)\n";
        cout << "  p (Create panorama with PTStitcher only with servo
            position)\n";
        cout << "  f (Find control points and create optimized panorama
            with PTStitcher)\n";
        cout << "  s (Create image series movie)\n";
        cout << "  q (Quit / Exit)\n";
        cin >> mode;
```

```
switch (mode) {

    case 'd': // Debug mode to see serial data only
    {
        cout << "Debug grabbing mode, without saving images. Roll
            all the way to exit\n";
        myserial.setupSerial();
        for(int i=1000;;i++) {
            if(counter == 20) { break; }
            // Sleep for 1 milliseconds
            struct timespec timeOut,remains;
            timeOut.tv_sec = 0;
            timeOut.tv_nsec = 1000000;
            nanosleep(&timeOut,&remains);
            // Count through milliseconds (raise counter every
                second)
            if(i==1000) {
                i=0;
                counter++;
            }
            // Grab serial data and output to console
            string somedata = myserial.
                returnSerialDataIfAvailable(true);
            // Exit if roll is greater than 0.8
            if(mybuf.getValue(2)>0.8) {
                break;
            }
        }
        myserial.closeSerial();
        break;
    }



    case 'g': // Grab images from camera and position info over
        Bluetooth
    {
        cout << "Grabbing images / pos info from cam, cancel with
            any key\n";
        myserial.setupSerial();
        cout << "Serial opened...\n";
        fcntl(0, F_GETFL, 0);                   // set read to
            non-blocking


        fcntl (0, F_SETFL, (tem | O_NDELAY));   // set read to
            non-blocking
        if(myserial.serialIsOk()) {
            while(true) {
                n = read(0, &c, 1);     // Check char input to
                    quit
                if (n > 0) { break; }   // (quit if any char is
                    pressed)
                cnt = cnt + 1;          // "
                // Grab serial data and send to Buffer
                mybuf.processInput(myserial.
                    returnSerialDataIfAvailable());
                if(mybuf.haveToGrabImage()) {
                    positionValues[0] = mybuf.getValue(0);
                    positionValues[1] = mybuf.getValue(1);
                    positionValues[2] = mybuf.getValue(2);
                    positionValues[3] = mybuf.getValue(3);
                    // Grab image from camera
                    mycam.grabImage(positionValues);
                    cout << "Grabbing image with pos info "<<
                        positionValues[0]<<"/"<<positionValues[1]
                        <<"/"<<positionValues[2]<<"/"<<
                        positionValues[3]<<"\n";
                }
                // break if recieve break signal from Buffer
                if(mybuf.haveToStop()) {
                    break;
                }
            }
        }
        else {
            cout << "Serial port opening failed...\n";
        }
        myserial.closeSerial();
        cout << "Serial closed...\n";
        break;
    }
```

```
case 'p': // Stitch using only servo angles
{
    timeval start, end; // Timer to see how long it takes
    gettimeofday(&start, 0); // "
    cout << "Converting pos info file to PTStitcher format\n"
        ;
    // Create Project.txt (Panotools compatible file)
    myfilemanip.convertInfoToPtstitcher(Settings::getSetting
        ("file_capture"),Settings::getSetting("file_project")
        );
    // Rearrange images to get right center
    myfilemanip.fixImagesCenter(Settings::getSetting
        ("file_project"));
    // Cut exceeding image and then create panorama
    myfilemanip.cutExceedingImages(Settings::getSetting

        ("file_project"),Settings::getSetting
        ("file_project_stitch"));
    cout << "Creating panorama using PTStitcher.\n";
    string ptscommand = Settings::getSetting
        ("path_ptstitcherng")+" -f "+Settings::getSetting
        ("file_project_stitch")+" -o "+Settings::getSetting
        ("folder_workdir")+"pano.jpeg";
    system(ptscommand.c_str());
    gettimeofday(&end, 0); // Timer to see how long it took
    double elapsedTime = ((double)end.tv_sec+(double)start.
        tv_usec/1000000)-((double)start.tv_sec+(double)end.
        tv_usec/1000000);
    cout << "\nExecution time: " << elapsedTime << " seconds\
        n\n";
    break;
}
```

```
case 'f': // Stitch using control points
{
    cout << "Please press 'n' for control points on neighbors
        only or any other key for control points on all
        images: ";
    char submode;
    cin >> submode;

    timeval start, end; // Timer to see how long it takes
    gettimeofday(&start, 0); // "

    cout << "Converting pos info file to PTStitcher format\n"
        ;
    myfilemanip.convertInfoToPtstitcher(Settings::getSetting
        ("file_capture"),Settings::getSetting
        ("file_controlpoints"));

    // Rearrange images to get right center
    myfilemanip.fixImagesCenter(Settings::getSetting
        ("file_controlpoints"));
    // Cut exceeding image and then create panorama (1)
    myfilemanip.cutExceedingImages(Settings::getSetting
        ("file_controlpoints"));
    // Make file read for control points
    myfilemanip.convertPtstitcherToCpfind(Settings::
        getSetting("file_controlpoints"),Settings::getSetting
        ("file_cpfind"));

    cout << "Finding control points\n";
    //string cpfcommand = Settings::getSetting("path_cpfind")
        +" --sieve1size 3 --minmatches 2 --kdtreesteps 10  -o
        "+Settings::getSetting("file_cpfind_out")+" "+
        Settings::getSetting("file_cpfind")+" ";
    string cpfcommand = "";
    // Only compare nearby images for control points
    if(submode=='n') { cpfcommand = Settings::getSetting

        ("path_cpfind")+" --multirow -o "+Settings::
        getSetting("file_cpfind_out")+" "+Settings::
        getSetting("file_cpfind"); }
    // Compare all images for control points
    else             { cpfcommand = Settings::getSetting
        ("path_cpfind")+" -o "+Settings::getSetting
        ("file_cpfind_out")+" "+Settings::getSetting
        ("file_cpfind"); }
    system(cpfcommand.c_str());

    cout << "Optimize with PToptimizer\n";
    myfilemanip.optimizeCpfindFile(Settings::getSetting
        ("file_cpfind_out"),Settings::getSetting
        ("file_optimizer"));
    // Execute optimizer to optimize control points (set new
        image positions)
    string cpocommand = Settings::getSetting
        ("path_ptoptimizer")+" "+Settings::getSetting
```

```
                    ("file_optimizer");
                system(cpocommand.c_str());
                cout << "Make ready for stitcher\n";
                myfilemanip.convertOptimizedToPtstitcher(Settings::
                    getSetting("file_optimizer"),Settings::getSetting
                    ("file_controlpoints"));

                // Rearrange images to get right center, also correct Yaw
                    to center panorama
                myfilemanip.fixImagesYawAndCenter(Settings::getSetting
                    ("file_controlpoints"),Settings::getSetting
                    ("folder_workdir")+"Project_stitch_points_centered.
                    txt");
                // Cut exceeding image and then create panorama
                myfilemanip.cutExceedingImages(Settings::getSetting
                    ("folder_workdir")+"Project_stitch_points_centered.
                    txt",Settings::getSetting("folder_workdir")+
                    "Project_stitch_points_cut.txt");
                cout << "Creating panorama using PTStitcher.\n";
                string fpcommand = Settings::getSetting
                    ("path_ptstitcherng")+" -o "+Settings::getSetting
                    ("folder_workdir")+"pano_controlpoints.jpeg "+
                    Settings::getSetting("folder_workdir")+
                    "Project_stitch_points_cut.txt";
                system(fpcommand.c_str());

                gettimeofday(&end, 0); // Timer to see how long it took
                double elapsedTime = ((double)end.tv_sec+(double)start.
                    tv_usec/1000000)-((double)start.tv_sec+(double)end.
                    tv_usec/1000000);
                cout << "\nExecution time: " << elapsedTime << " seconds\
                    n";
                if(submode=='a') { cout << "for control points on all
                    images\n\n"; }
                if(submode=='n') { cout << "for control points on
                    neighbor images\n\n"; }
                break;
            }




            case 's': // Create image series movie
            {
                cout << "Converting pos info file to PTStitcher format\n"
                    ;
                // Create Project.txt (Panotools compatible file)
                myfilemanip.convertInfoToPtstitcher(Settings::getSetting
                    ("file_capture"),Settings::getSetting("file_project")
                    );
                // Cut exceeding image and then create panorama (1)
                myfilemanip.cutExceedingImages(Settings::getSetting
                    ("file_project"));
                // Get total image amount
                int imgamount = myfilemanip.getImageAmountFromFile
                    (Settings::getSetting("file_project"));
                cout << imgamount << " images total for series\n";
                for(int i=0;i<=imgamount;i++) {
                    // Cut to desired amount of images (always
                        incrementing)
                    myfilemanip.cutExceedingImages(Settings::getSetting
                        ("file_project"),Settings::getSetting
                        ("file_series"),i);
                    string number = "";
                    if(i<1000) { number +="0"; }
                    if(i<100)  { number +="0"; }
                    if(i<10)   { number +="0"; }
                    number+=Utils::intToString(i);
                    // Stitch always one more image to the panorama
                    string ptscommand = Settings::getSetting
                        ("path_ptstitcherng")+" -o "+Settings::getSetting
                        ("folder_series")+"img"+number+".jpeg "+Settings
                        ::getSetting("file_series");
                    system(ptscommand.c_str());
                }
                // Create a movie using ffmpeg
                string sercommand = Settings::getSetting("path_ffmpeg")+"
                    -r 5 -b 18000 -i "+Settings::getSetting
                    ("folder_series")+"img%04d.jpeg "+Settings::
                    getSetting("folder_workdir")+"series.avi";
                system(sercommand.c_str());
                break;
            }
            default:
                break;
        }
    }
    return 0;
}
```

E.2 SerialConnection.h

```
/*  SerialConnection.h - PanoProcessor
 *  Created by Lukas Pfirter on 13.05.11.
 *  Contains functions to setup a serial connection and
 *  read data as a string from the connection. */
#include <termios.h>
#include <string.h>
using namespace std;

class SerialConnection {
    // Variables for the serial connection
    struct termios tio,stdio; // Serial options carrier
    int tty_fd; // Serial handle
    //fd_set rdset; //
    //int res;
    int bytes_avaiable; // What is available
    int readamount; // What we're reading
    string serialadapter; // Adapter, e.g.: "/dev/tty.PL2303-0000201A"

public:
    SerialConnection(string adapter=""); // Constructor, sets the adapter
        string
    void setupSerial(); // Setup function to call before reading
    string returnSerialDataIfAvailable(bool debug=false); // Returns data
        if available
    void closeSerial(); // Function to call at program quit
    void readSerialDataDebug(SerialConnection myserial); // Serial read
        function for debug
    bool serialIsOk(); // Returns true if serial is connected
};
```

E.3 FileManipulator.h

```
/*  FileManipulator.h - PanoProcessor
 *  Created by Lukas Pfirter on 13.05.11.
 *  Div. functions for reading files / writing to files */
#include <fstream>
#include <iostream>
#include <iomanip>
#include <string>
using namespace std;

class FileManipulator {

    int ymin,ymax,pmin,pmax; // Border values for pitch/yaw in panorama
        creation for PTStitcherNG

public:

    FileManipulator(int yminvalue,int ymaxvalue,int pminvalue,int
        pmaxvalue); // Constructor sets border values for pitch/yaw

    void convertInfoToPtstitcher(string infofilename, string ptfilename);
        // Converts a file created by CamHandler::grabImage to the
        PTStitcher format
    void convertPtstitcherToCpfind(string ptfilename,string cpfilename);

    void optimizeCpfindFile(string cpfindoutfile,string optimizedfile);
    void convertOptimizedToPtstitcher(string optimizedfilename, string
        ptfilename);

    void cutExceedingImages(string inFile, string outFile="", int
        imglimit=9999);
    void fixImagesCenter(string file);
    void fixImagesYawAndCenter(string inFilename, string outFilename="");

    int getImageAmountFromFile(string filename); // Function to count o-
        lines (amount of images) from Project file

    void writeToFile(string filename, string content); // Write content
        to file
    string readFromFile(string filename); // Return whole filecontent as
        string

};
```

E.4 Utils.h

```
/*  Utils.h - PanoProcessor
 *  Created by Lukas Pfirter on 17.05.11.
 *  Contains diverse helping functions
 *  in a static class. */

#include <string>
#include <vector>

using namespace std;

class Utils {

public:
    static string doubleToString(double d); // Convert double to string
    static string intToString(int number);  // Convert int to string
    // Check cpp file for explanation of the following functions:
    static string eraseStringPart(string str, string erasePattern);
    static double getLineValueFromIdentifier(string line, char identifier
        );
    static string getLineValueFromIdentifierAsString(string line, char
        identifier);
    // Explode / Split string by a certain separator, save in results
    static void StringExplode(string str, string separator, vector<string
        >* results);

};
```

E.5 BufferManager.h

```
/*  BufferManager.h - PanoProcessor
 *  Created by Lukas Pfirter on 11.05.11. */
using namespace std;

class BufferManager {

    double data[10];    // Holds data from microcontroller and gets
        actualized
                        // data[0]  ->  RC_THROTTLE
                        // data[1]  ->  RC_ROLL
                        // data[2]  ->  RC_PITCH
                        // data[3]  ->  RC_YAW

    int grabImage;      // If HIGH (1) grab an image
    int run;            // If LOW (0) stop grabbing

    string thebuffer;   // Holds the current buffer
    string wholebuffer; // Holds all that ever was received from serial
        (for debug only)

public:

    BufferManager(); // Constructor

    void processInput(string input, bool debug=false);

    void printInfo(); // For Debug only (prints all variables)
    void writeBufferToFile(string filename); // For Debug only (writes "
        wholebuffer" to a file

    double getValue(int position); // Get value of data array
    double *getValues(); // Returns the whole data array

    bool haveToGrabImage();
    bool haveToStop();

private:

    void saveInfo(string info, bool debug=false);

};
```

E.6 CamHandler.h

```
/*  CamHandler.h - PanoProcessor
 *  Created by Lukas Pfirter on 13.05.11. */
using namespace std;

class CamHandler {

    int imagenumber;                        // Number of next image,
        counter of saved images
    string loc_wget;                        // Location of wget
    string link_camimg;                     // Link of Cam image
    string link_imgsavepath;                // Image save locations

public:

    CamHandler(string ip, string savelocation, string wgetpath, string
        camuser, string campw); // Constructor

    void grabImage(double *positionValues); // Function that captures
        image and saves it

private:

    //string doubleToString(double d);

};
```

E.7 Settings.h

```
/*  Settings.h - PanoProcessor
 *  Created by Lukas Pfirter on 16.05.11.
 *  Contains all the paths and other
 *  settings for the PanoProcessor. */
#include <string>
using namespace std;
class Settings {
public:
    static string getSetting(string identifier); // Return setting value
};
string Settings::getSetting(string id) {
    // Set workdir to where we save and process images:
    string workdir = "/Users/g4lp/Desktop/Capture/";
    // Paths of used command line applications
    if      (id=="path_ptstitcherng") { return "/Applications/
        PTStitcherNG0.7b/PTStitcherNG"; }
    else if (id=="path_ptoptimizer"){ return "/Applications/Hugin.app/
        Contents/MacOS/PToptimizer"; }
    else if (id=="path_cpfind")     { return "/Applications/Hugin.app/
        Contents/MacOS/cpfind"; }
    else if (id=="path_ffmpeg")     { return "/opt/local/bin/ffmpeg"; }
    else if (id=="path_wget")       { return "/opt/local/bin/wget"; }
    // Paths to used text files / project files and folders (with
        trailing slash)
    else if (id=="folder_workdir")  { return workdir; }
    else if (id=="folder_series")   { return workdir+"Series/"; }
    else if (id=="file_capture")    { return workdir+"capture.txt"; }
    else if (id=="file_project")    { return workdir+"Project.txt"; }
    else if (id=="file_project_stitch") { return workdir+
        "Project_stitchonly.txt"; }
    else if (id=="file_series")     { return workdir+"Project_series.txt"
        ; }
    else if (id=="file_controlpoints") { return workdir+
        "Project_stitch_points.txt"; }
    else if (id=="file_cpfind")     { return workdir+"Project_cpfind.txt"
        ; }
    else if (id=="file_cpfind_out") { return workdir+"Project_cpfind_out.
        txt"; }
    else if (id=="file_optimizer")  { return workdir+"Project_optimizer.
        txt"; }
    // Serial adapter, Camera
    else if (id=="serial_bluetooth"){ return "/dev/tty.CoaX_0000-COM1"; }
        // Serial bluetooth
    else if (id=="serial")          { return "/dev/tty.PL2303-0000201A";
        } // Regular serial
    else if (id=="camera_ip_eth")   { return "192.168.0.90"; }
    else if (id=="camera_ip_wlan")  { return "192.168.1.4"; }
    else if (id=="camera_user")     { return "root"; }
    else if (id=="camera_password") { return "test1234"; }
    else { return ""; }
}
```

E.8 Microcontroller program

Include into main():

```
// Start capturing images
sprintf(message,"[start@start]\n");
broadcast_message(message);
// Starting position for camera
MOTOR_SetServoAngle(0, 0.5);
__delay32(_500MILLISEC*20);
// Set initial values for pan/tilt angles
double throttle=0;
double b=-0.8;
double lastthrottle=0;
double lastb=-0.8;
__delay32(_100MILLISEC*10);
int ii=1;
// move throttle from 0 until 0.9
// And b from -0.8 until 0.8
while(throttle <= 0.90) {
        if(ii==1) {
                b=-0.8;
                while(b <= 0.8) {
                        lastb=b;
                        b += 0.05;
                        imagecapture(b,throttle,lastb,lastthrottle,
                             message);
                }
        }
        else {
                double b=0.8;
                while(b >= -0.8) {
                        lastb=b;
                        b -= 0.05;
                        imagecapture(b,throttle,lastb,lastthrottle,
                             message);
                }
        }
        ii*=-1;
        lastthrottle=throttle;
        throttle += 0.1;
}
__delay32(_100MILLISEC);
// Stop capturing images
sprintf(message,"[stop@stop]\n");
broadcast_message(message);
```

Include above main():

```
// Function to capture an image at the desired position
void imagecapture(double b,double throttle,double lastb,double
    lastthrottle,char *message) {
        double iterateb=0;
        double schritt=0.001;
        if(lastb<b) { // Move from left to right
                while(lastb+iterateb<b) {
                        // Set servos to desired angles
                        MOTOR_SetServoAngle(lastb+iterateb, throttle);
                        MOTOR_SetSpeed(lastb+iterateb,throttle);
                        iterateb+=schritt;
                        __delay32(_10MILLISEC);
                }
        }
        else { // Move from right to left
                while(lastb-iterateb>b) {
                        // Set servos to desired angles
                        MOTOR_SetServoAngle(lastb-iterateb, throttle);
                        MOTOR_SetSpeed(lastb-iterateb,throttle);
                        iterateb+=schritt;
                        __delay32(_10MILLISEC);
                }
        }
        //__delay32(_100MILLISEC);
        sprintf(message,"[th@%.2f]",throttle);
        broadcast_message(message);
        sprintf(message,"[ro@%.2f]",b);
        broadcast_message(message);
        sprintf(message,"[grab@grab]\n");
        broadcast_message(message);
        __delay32(_100MILLISEC);
}
```